On the Decidability of Subtyping with Bounded Existential Types*

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Abstract. Bounded existential types are a powerful language feature for modeling partial data abstraction and information hiding. However, existentials do not mingle well with subtyping as found in current object-oriented languages: the subtyping relation is already undecidable for very restrictive settings.
This paper considers two subtyping relations defined by extracting the features specific to existentials from current language proposals (JavaGI, WildFJ, and Scala) and shows that both subtyping relations are undecidable. One of the two subtyping relations remains undecidable even if bounded existential types are removed.
With the goal of regaining decidable type checking for the JavaGI language, the paper also discusses various restrictions including the elimination of bounded existentials from the language as well as possible amendments to regain some of their features.

1 Introduction

Cardelli and Wegner [5] introduced bounded existential types to obtain a fine-grained modeling instrument for structured and partial data abstraction and information hiding, thus generalizing the concept of an abstract data type modeled with a plain existential type [12]. Language designers and type theorists rely on bounded existentials in diverse areas such as object-oriented languages [1], module systems [19], and functional languages [10].

In the realm of object-oriented languages, bounded existential types have found uses for modeling object-oriented languages in general [2], as well as for modeling specific features such as Java wildcards [3,20,21]. Only a few languages (e.g., Scala [13]) make bounded existential types in full generality available to the programmer. Also, the initial design of JavaGI [23] includes bounded existential types and provides interface types (i.e., the ability to form types from interface names) as a special case supported by syntactic sugar. Building directly on bounded existential types has several advantages compared to interface types: they properly generalize interface types, they encompass Java wildcards, and they have meaningful uses with interfaces abstracting over families of types. Thus, despite the complexity that they introduce in a type system, bounded existential types initially appear like a worthwhile feature.

* A preliminary version of this work was presented at FTfJP 2008 [24].

Unfortunately, it turns out that subtyping —and hence type checking— for JavaGI is undecidable in the presence of general bounded existential types. Furthermore, subtyping for bounded existential types as used to encode Java wildcards is also undecidable. This article proves both of these undecidability results. Moreover, it also shows that replacing JavaGI's existentials with plain interface types does not regain decidability of subtyping.

Contributions and Overview

After refreshing some background on the JavaGI language in Sec. 2, Sec. 3 defines the calculus $\mathcal{EX}_{impl}$ that models the essential aspects of subtyping and bounded existential types in JavaGI. Subtyping in $\mathcal{EX}_{impl}$ is shown to be undecidable by reduction from Post's Correspondence Problem [18]. Further, the section defines the calculus $\mathcal{IT}_{impl}$ by replacing existential types in $\mathcal{EX}_{impl}$ with plain interface types. Subtyping in $\mathcal{IT}_{impl}$ is also undecidable but various restrictions exist that ensure decidability.

Sec. 4 considers the calculus $\mathcal{EX}_{uplo}$ supporting existentials with lower and upper bounds. Subtyping in $\mathcal{EX}_{uplo}$ is also undecidable, as shown by reduction from subtyping in $F^D_{\leq}$, a restricted form of the polymorphic λ-calculus extended with subtyping [14]. The results in this section are relevant to Scala [13], formal systems for modeling Java wildcards [3, 4, 20], and JavaGI's full type system.

Sec. 5 explores alternative design options for JavaGI that avoid bounded existential types but keep the remaining features. Finally, Sec. 6 reviews related work and Sec. 7 concludes. Detailed proofs may be found in the appendices.

2 Background

JavaGI [23, 25] is a conservative extension of Java 1.5. It generalizes Java's interface concept to incorporate the essential features of Haskell type classes [8, 22]. The generalization allows for retroactive and type-conditional interface implementations, binary methods, static methods in interfaces, default implementations for interface methods, and multi-headed interfaces (interfaces over families of types). Furthermore, JavaGI's initial design generalizes Java-like interface types to bounded existential types. This section only discusses the features relevant to this paper, namely retroactive interface implementations and existential types.

2.1 Retroactive Interface Implementations

Retroactive interface implementations allow programmers to implement an interface for some class without changing the source code of the class. For example, Java rejects the use of a `for`-loop to iterate over the characters of a string because the class `String` does not implement the interface `Iterable`:[1]

[1] Java's enhanced `for`-loop allows to iterate over arrays and all types implementing the `Iterable<X>` interface, which contains a single method `Iterator<X> iterator()`.

```
implementation Iterable<Character> [String] {
  public Iterator<Character> iterator() {
    return new Iterator<Character>() {
      private int index = 0;
      public boolean hasNext() { return index < length(); }
      public Character next() { return charAt(index++); }
    };
  }
}
```

Fig. 1. Retroactive implementation of the `Iterable` interface.

```
for (Character c : "21 is only half the truth") { ... } // illegal in Java
```

As a class definition in Java must specify all interfaces that the class implements and the definition of `java.lang.String` is fixed, there is no hope of getting this code to work. A JavaGI programmer can overcome this restriction by adding implementations for interfaces to an existing class at any time, retroactively, without modifying the source code of the class.

For example, the *implementation definition* shown in Fig. 1 specifies that the *implementing type* `String`, enclosed in square brackets `[]`, implements the interface `Iterable<Character>`.[2] The definition of the `iterator` method can use the methods `length` and `charAt` because they are part of `String`'s public interface.

2.2 Bounded Existential Types

Java uses the name of an interface as an *interface type* to denote the set of all types implementing the interface. Instead of interface types, the initial design of JavaGI features *bounded existential types* [5] and provides syntactic sugar for recovering interface types. For example, the interface type `List<String>` abbreviates the existential type ∃ `X where X implements List<String> . X`. The *implementation constraint* "`X implements List<String>`" restricts instantiations of the type variable `X` to types that implement the interface `List<String>`. Thus, the existential type denotes the set of all types implementing `List<String>`, exactly like the synonymous interface type. (The occurrence of "`List<String>`" in the implementation constraint does not abbreviate an existential type.)

Existentials are more general than interface types. For instance, the existential ∃ `X where X implements List<String>, X implements Set<String> . X` denotes the set of all types that implement both `List<String>` and `Set<String>`. Java supports such intersections of interface types only for specifying bounds of type variables. Existentials also encompass Java wildcards [3, 4, 20, 21]. For instance, the existential type ∃ `X where X extends Number . List<X>` corresponds to the wildcard type `List<? extends Number>`.[3]

[2] The implementation ignores the `remove` method of the `Iterator` interface.

[3] Because `List` is an interface, ∃ `X where X extends Number . List<X>` stands for ∃ `X,L where X extends Number, L implements List<X> . L`.

Syntax

$$P, Q, R ::= X\ \texttt{implements}\ I\texttt{<}\overline{T}\texttt{>}$$
$$T, U, V, W ::= X \mid \exists X\ \texttt{where}\ P\,.\,X$$
$$def ::= \texttt{interface}\ I\texttt{<}\overline{X}\texttt{>} \mid \texttt{implementation<}\overline{X}\texttt{>}\ I\texttt{<}\overline{T}\texttt{>}\ \texttt{[}I\texttt{<}\overline{T}\texttt{>]}$$
$$X, Y, Z \in \mathit{TyvarName} \qquad I, J \in \mathit{IfaceName}$$

$\boxed{\Theta; \Delta \Vdash T\ \texttt{implements}\ I\texttt{<}\overline{T}\texttt{>}}$

$$\text{E}_1\text{-IMPL}\ \frac{\texttt{implementation<}\overline{X}\texttt{>}\ I\texttt{<}\overline{T}\texttt{>}\ \texttt{[}U\texttt{]} \in \Theta}{\Theta; \Delta \Vdash [\overline{V}/\overline{X}]\,(U\ \texttt{implements}\ I\texttt{<}\overline{T}\texttt{>})} \qquad \text{E}_1\text{-LOCAL}\ \frac{P \in \Delta}{\Theta; \Delta \Vdash P}$$

$\boxed{\Theta; \Delta \vdash T \leq T}$

$$\text{S}_1\text{-REFL}\ \Theta; \Delta \vdash T \leq T \qquad \text{S}_1\text{-TRANS}\ \frac{\Theta; \Delta \vdash T \leq U \qquad \Theta; \Delta \vdash U \leq V}{\Theta; \Delta \vdash T \leq V}$$

$$\text{S}_1\text{-OPEN}\ \frac{\Theta; \Delta, P \vdash X \leq T \qquad X \notin \mathsf{ftv}(\Theta, \Delta, T)}{\Theta; \Delta \vdash (\exists X\ \texttt{where}\ P\,.\,X) \leq T} \qquad \text{S}_1\text{-ABSTRACT}\ \frac{\Theta; \Delta \Vdash [T/X]P}{\Theta; \Delta \vdash T \leq (\exists X\ \texttt{where}\ P\,.\,X)}$$

Fig. 2. Syntax, entailment, and subtyping for $\mathcal{EX}_{impl}$.

The initial design of JavaGI allows implementation definitions for existentials. For example, given an interface `I`, a programmer may write an implementation definition to specify that all types implementing `List<X>` also implement `I`.

```
implementation<X> I [List<X>] { /* implement methods of I */ }
```

Such a definition is feasible only if all methods of `I` can be implemented using only methods of the `List` interface. The example also demonstrates that JavaGI supports *generic implementation definitions*, which are parameterized by type variables.

3 Subtyping Existential Types with Implementation Constraints

This section introduces $\mathcal{EX}_{impl}$, a subtyping calculus with existentials ($\mathcal{EX}$) and implementation constraints (*impl*). The calculus is a subset of Core-JavaGI [23]. It does not model all aspects of JavaGI's initial design, but contains only those features that make subtyping undecidable. In particular, the syntax of existentials is restricted such that all existentials are encodings of interface types. Consequently, undecidability of subtyping also holds for $\mathcal{IT}_{impl}$, a variant of $\mathcal{EX}_{impl}$ where interface types ($\mathcal{IT}$) replace existentials.

3.1 Definition of $\mathcal{EX}_{impl}$

Fig. 2 defines the syntax along with the entailment and subtyping relations of $\mathcal{EX}_{impl}$. An implementation constraint P has the form $X\ \texttt{implements}\ I\texttt{<}\overline{T}\texttt{>}$ and

constrains the type variable X to types that implement the interface $I\texttt{<}\overline{T}\texttt{>}$. An interface without type parameters is written I instead of $I\texttt{<}\bullet\texttt{>}$.[4]

A type T is either a type variable X or a bounded existential type of the form $\exists X\,\texttt{where}\,X\,\texttt{implements}\,I\texttt{<}\overline{T}\texttt{>}\,.\,X$. For simplicity, there are no class types, existentials have a single quantified type variable X, they have exactly one constraint $X\,\texttt{implements}\,I\texttt{<}\overline{T}\texttt{>}$, and the body of an existential must be the quantified type variable. Existentials are considered equal up to renaming of bound type variables.

A definition *def* in $\mathcal{EX}_{impl}$ is either an interface or an implementation definition. Interface and implementation definitions do not have method signatures or bodies, because methods do not matter for the entailment and subtyping relations of $\mathcal{EX}_{impl}$. Moreover, $\mathcal{EX}_{impl}$ does not support interface inheritance. An implementation definition $\texttt{implementation<}\overline{X}\texttt{>}\ I\texttt{<}\overline{T}\texttt{>}\ \texttt{[}J\texttt{<}\overline{U}\texttt{>]}$ implicitly assumes that $\overline{X} = \mathsf{ftv}(J\texttt{<}\overline{U}\texttt{>})$.[5]

The entailment relation $\Theta; \Delta \Vdash T\,\texttt{implements}\,I\texttt{<}\overline{T}\texttt{>}$ expresses that type T implements interface $I\texttt{<}\overline{T}\texttt{>}$. It relies on a program environment Θ, which is a finite set of definitions *def*, and a type environment Δ, which is a finite set of constraints P, where Δ, P abbreviates $\Delta \cup \{P\}$. A type implements an interface either because it corresponds to an instance of a suitable implementation definition (rule E$_1$-IMPL) or because the type environment contains the constraint (rule E$_1$-LOCAL).[6]

The subtyping relation $\Theta; \Delta \vdash T \leq U$ states that T is a subtype of U. It is reflexive and transitive as usual. Rule S$_1$-OPEN opens an existential on the left-hand side of the subtyping relation by moving its constraint into the type environment. The premise $X \notin \mathsf{ftv}(\Theta, \Delta, T)$ ensures that the existentially quantified type variable is sufficiently fresh and does not escape from its scope. Rule S$_1$-ABSTRACT deals with existentials on the right-hand side of the subtyping relation. It states that T is a subtype of some existential if the constraint of the existential holds after substituting T for the existentially quantified type variable.

As part of a type soundness proof for Core-JavaGI, we verified that the subtyping relation of $\mathcal{EX}_{impl}$ supports the usual principle of subsumption: we can always promote the type of an expression to some supertype without causing runtime errors.

3.2 Undecidability of Subtyping in $\mathcal{EX}_{impl}$

The undecidability of subtyping in $\mathcal{EX}_{impl}$ follows by reduction from Post's Correspondence Problem (PCP). It is well known that PCP is undecidable [7, 18].

Definition 1 (PCP). *Let $\{(u_1, v_1) \ldots, (u_n, v_n)\}$ be a set of pairs of non-empty words over some finite alphabet Σ with at least two elements. A solution of PCP*

[4] The notation $\overline{\xi}$ abbreviates a sequence $\xi_1, \ldots, \xi_n$ of syntactic entities with $\bullet$ standing for the empty sequence. Sometimes, the sequence $\overline{\xi}$ stands for the set $\{\overline{\xi}\}$.

[5] The notation $\mathsf{ftv}(\xi)$ denotes the set of type variables free in ξ.

[6] The notation $[\overline{T/X}]$ stands for the capture-avoiding substitution replacing each X_i with T_i.

is a sequence of indices $i_1 \dots i_r$ such that $u_{i_1} \dots u_{i_r} = v_{i_1} \dots v_{i_r}$. The decision problem asks whether such a solution exists.

Theorem 2. *Subtyping in $\mathcal{EX}_{impl}$ is undecidable.*

Proof. Let $\mathcal{P} = \{(u_1, v_1), \dots, (u_n, v_n)\}$ be a particular instance of PCP over the alphabet Σ. We can encode $\mathcal{P}$ as an equivalent subtyping problem in $\mathcal{EX}_{impl}$ as follows. First, words over Σ must be represented as types in $\mathcal{EX}_{impl}$.

```
interface E       // empty word ε
interface L<X>    // letter, for every L ∈ Σ
```

Words $u \in \Sigma^*$ are formed with these interfaces through nested existentials. For example, the word `AB` is represented by

$$\exists X \texttt{ where } X \texttt{ implements A<}\exists Y \texttt{ where } Y \texttt{ implements B<} \\ \exists Z \texttt{ where } Z \texttt{ implements E} \,.\, Z\texttt{>} \,.\, Y\texttt{>} \,.\, X$$

The abbreviation $I\texttt{<}\overline{T}\texttt{>}$ stands for the type $\exists X \texttt{ where } X \texttt{ implements } I\texttt{<}\overline{T}\texttt{>} \,.\, X$. Using this notation, the word `AB` is represented by `A<B<E>>`.

Formally, we define the representation of a word u as $[\![u]\!] := u \,\#\, \texttt{E}$, where $u \,\#\, T$ is the concatenation of a word u with a type T:

$$\varepsilon \,\#\, T := T \qquad\qquad Lu \,\#\, T := L\texttt{<}u \,\#\, T\texttt{>}$$

Two interfaces are required to model the search for a solution of PCP:

```
interface S<X,Y>    // search state
interface G         // search goal
```

The type $\texttt{S<}[\![u]\!], [\![v]\!]\texttt{>}$ represents a particular search state where we have already accumulated indices $i_1, \dots, i_k$ such that $u = u_{i_1} \dots u_{i_k}$ and $v = v_{i_1} \dots v_{i_k}$. To model valid transitions between search states, we define implementations of `S` for all $i \in \{1, \dots, n\}$ as follows:

$$\texttt{implementation<X,Y> S<}u_i\texttt{\#X, }v_i\texttt{\#Y> [S<X,Y>]} \tag{1}$$

The type `G` represents the goal of a search, as expressed by the following implementation:

$$\texttt{implementation<X> G [S<X,X>]} \tag{2}$$

To get the search running we ask whether there exists some $i \in \{1, \dots, n\}$ such that $\Theta_{\mathcal{P}}; \emptyset \vdash \texttt{S<}[\![u_i]\!], [\![v_i]\!]\texttt{>} \leq \texttt{G}$ is derivable. The program $\Theta_{\mathcal{P}}$ consists of the interfaces and implementations just defined. In Appendix A, we prove a lemma showing that $\mathcal{P}$ has a solution if, and only if, there exists some $i \in \{1, \dots, n\}$ such that $\Theta_{\mathcal{P}}; \emptyset \vdash \texttt{S<}[\![u_i]\!], [\![v_i]\!]\texttt{>} \leq \texttt{G}$ is derivable. □

Example. Suppose the PCP instance $\mathcal{P} = \{(u_1, v_1), (u_2, v_2)\}$ with $u_1 = \texttt{A}$, $u_2 = \texttt{ABA}$, $v_1 = \texttt{AA}$, and $v_2 = \texttt{B}$ is given. The instance has the solution $1, 2, 1$ because $u_1 u_2 u_1 = v_1 v_2 v_1 = \texttt{AABAA}$. The program $\Theta_{\mathcal{P}}$ for the $\mathcal{EX}_{impl}$ encoding of this problem looks like this:

Syntax

$$\varphi ::= \forall \overline{X}.\, I\texttt{<}\overline{T}\texttt{>} \le I\texttt{<}\overline{T}\texttt{>}$$
$$T, U, V, W ::= X \mid I\texttt{<}\overline{T}\texttt{>}$$
$$X, Y, Z \in \mathit{TyvarName} \qquad I, J \in \mathit{IfaceName}$$

$\Phi \vdash T \le T$

$$\text{S}_2\text{-REFL}\ \ \Phi \vdash T \le T \qquad \text{S}_2\text{-TRANS}\ \ \frac{\Phi \vdash T \le U \qquad \Phi \vdash U \le V}{\Phi \vdash T \le V} \qquad \text{S}_2\text{-IMPL}\ \ \frac{(\forall \overline{X}.\, T \le U) \in \Phi}{\Phi \vdash [\overline{V/X}]T \le [\overline{V/X}]U}$$

Fig. 3. Syntax and subtyping for $\mathcal{IT}_{impl}$.

```
interface E          interface A<X>    interface B<X>
interface S<X,Y>     interface G
implementation<X,Y> S<A<X>,       A<A<Y>>>  [S<X,Y>]      // (1)
implementation<X,Y> S<A<B<A<X>>>, B<Y>>     [S<X,Y>]      // (2)
implementation<X>   G                       [S<X,X>]      // (3)
```

We then need to ask whether there exists some $i \in \{1, 2\}$ such that $\Theta_{\mathcal{P}}; \emptyset \vdash \texttt{S<}[\![u_i]\!], [\![v_i]\!]\texttt{>} \le \texttt{G}$ is derivable. Verifying that such a derivation exists for $i = 1$ is left as an exercise to the reader.

3.3 Undecidability Without Existential Types

The proof of undecidability of subtyping in $\mathcal{EX}_{impl}$ reveals that subtyping remains undecidable even if plain interface types replace existentials. To make this claim concrete, Fig. 3 defines the calculus $\mathcal{IT}_{impl}$, which essentially is a version of $\mathcal{EX}_{impl}$ with plain interface types instead of existentials. The simplify the syntax, $\mathcal{IT}_{impl}$ drops interface definitions altogether and uses subtyping schemes instead of implementation definitions: a *subtyping scheme* $\varphi = \forall \overline{X}.\, J\texttt{<}\overline{T}\texttt{>} \le I\texttt{<}\overline{U}\texttt{>}$ corresponds to an implementation definition `implementation<`$\overline{X}$`>` $I\texttt{<}\overline{U}\texttt{>}$ `[`$J\texttt{<}\overline{T}\texttt{>}$`]`. Such a subtyping scheme implicitly assumes that $\overline{X} = \mathsf{ftv}(J\texttt{<}\overline{T}\texttt{>})$. $\mathcal{IT}_{impl}$ also replaces constraint entailment and the rules S_1-OPEN and S_1-ABSTRACT with a single rule S_2-IMPL. The symbol Φ ranges over finite sets of subtyping schemes φ.

Theorem 3. *Subtyping in $\mathcal{IT}_{impl}$ is undecidable.*

Proof. Similar to the proof of Theorem 2.

The rest of this section investigates decidable fragments of $\mathcal{IT}_{impl}$. It starts with the observation that the undecidability proofs of subtyping in $\mathcal{EX}_{impl}$ and $\mathcal{IT}_{impl}$ rely on two main ingredients:

Cyclic interface subtyping. Implementation definitions in $\mathcal{EX}_{impl}$ (or subtyping schemes in $\mathcal{IT}_{impl}$) allow the introduction of cycles in the subtyping graph of interfaces. Consider one of the implementations defined by Equation (1) on page 6: it states that $\texttt{S<}u_i \,\#\, \texttt{X}, v_i \,\#\, \texttt{Y>}$ is a supertype of `S<X,Y>`. In the reduction from PCP, such cycles are used to encode the individual steps in the search for a solution.

Multiple instantiation subtyping. Implementation definitions in $\mathcal{EX}_{impl}$ (or subtyping schemes in $\mathcal{IT}_{impl}$) allow to introduce two different instantiations of the same interface as supertypes of some other interface. Consider again the implementations defined by Equation (1): for $u_i \neq u_j$ or $v_i \neq v_j$ the implementations state that $\texttt{S<}u_i \# \texttt{X}, v_i \# \texttt{Y>} \neq \texttt{S<}u_j \# \texttt{X}, v_j \# \texttt{Y>}$ are both supertypes of $\texttt{S<X,Y>}$. In the reduction from PCP, multiple instantiation subtyping encodes the choice between different pairs (u_i, v_i) and (u_j, v_j).

An obvious way to obtain decidable subtyping for $\mathcal{IT}_{impl}$ is to restrict the set of subtyping schemes Φ such that, for all types T, only a finite set of T-supertypes is derivable from Φ.

Definition 4. *The* set of T-supertypes derivable from Φ*, written* $\mathcal{S}_{T,\Phi}$*, is defined as the smallest set closed under the following rules:*

$$T \in \mathcal{S}_{T,\Phi} \qquad \frac{(\forall \overline{X}.\, V \leq U) \in \Phi \qquad [\overline{W/X}]V \in \mathcal{S}_{T,\Phi}}{[\overline{W/X}]U \in \mathcal{S}_{T,\Phi}}$$

Restriction 1. The set $\mathcal{S}_{T,\Phi}$ must be finite for all types T.

Theorem 5. *Under Restriction 1, subtyping in* $\mathcal{IT}_{impl}$ *is decidable.*

Proof. See Appendix B. □

Here is a restriction that eliminates cyclic interface subtyping.

Definition 6. *A finite set of subtyping schemes* Φ *is contractive if, and only if, there exists no sequence* $\varphi_1, \ldots, \varphi_n \in \Phi$ *such that* $\varphi_i = \forall \overline{X_i}.\, I_i\texttt{<}\overline{T_i}\texttt{>} \leq J_i\texttt{<}\overline{U_i}\texttt{>}$ *for all* $i = 1, \ldots, n$ *and* $J_i = I_{i+1}$ *for all* $i = 1, \ldots, n-1$ *and* $J_n = I_1$*.*

Restriction 2. The set Φ must be contractive.

Lemma 7. *Restriction 2 implies Restriction 1.*

Proof. See Appendix C. □

Remark. Restriction 1 does not imply Restriction 2. Consider the set $\Phi = \{\forall \bullet . I \leq I\}$, which obviously meets Restriction 1 but is not contractive.

The next restriction is strictly stronger than Restriction 2.

Restriction 3. For all $\varphi_1, \varphi_2 \in \Phi$ is must hold that $\varphi_1 = \forall \overline{X}.\, I_1\texttt{<}\overline{T}\texttt{>} \leq J_1\texttt{<}\overline{U}\texttt{>}$ and $\varphi_2 = \forall \overline{Y}.\, I_2\texttt{<}\overline{V}\texttt{>} \leq J_2\texttt{<}\overline{W}\texttt{>}$ imply $J_1 \neq I_2$.

The last restriction considered eliminates multiple instantiation subtyping.

Restriction 4. If $\Phi \vdash I\texttt{<}\overline{T}\texttt{>} \leq J\texttt{<}\overline{U}\texttt{>}$ and $\Phi \vdash I\texttt{<}\overline{T}\texttt{>} \leq J\texttt{<}\overline{V}\texttt{>}$ then it must hold that $\overline{U} = \overline{V}$.

Lemma 8. *Restriction 4 implies Restriction 1.*

Proof. See Appendix C. □

Remark. Neither Restriction 1 nor Restriction 2 implies Restriction 4 as demonstrated by $\Phi = \{\forall \bullet . I \leq J\texttt{<}A\texttt{>}, \forall \bullet . I \leq J\texttt{<}B\texttt{>}\}$. Moreover, Restriction 4 does not imply Restriction 2 as demonstrated by $\Phi' = \{\forall \bullet . I \leq J, \forall \bullet . J \leq I\}$.

Syntax

$$N, M ::= C\texttt{<}\overline{X}\texttt{>} \mid \texttt{Object}$$
$$T, U, V, W ::= X \mid N \mid \exists \overline{X}\,\texttt{where}\,\overline{P}\,.\,N$$
$$P, Q, R ::= X\,\texttt{extends}\,T \mid X\,\texttt{super}\,T$$
$$X, Y, Z \in \mathit{TyvarName} \qquad C, D \in \mathit{ClassName}$$

$\Delta \Vdash T\,\texttt{extends}\,T \qquad \Delta \Vdash T\,\texttt{super}\,T$

$$\text{E3-EXTENDS}\ \frac{\Delta \vdash T \le U}{\Delta \Vdash T\,\texttt{extends}\,U} \qquad \text{E3-SUPER}\ \frac{\Delta \vdash U \le T}{\Delta \Vdash T\,\texttt{super}\,U}$$

$\Delta \vdash T \le T$

$$\text{S3-REFL}\ \Delta \vdash T \le T \qquad \text{S3-TRANS}\ \frac{\Delta \vdash T \le U \quad \Delta \vdash U \le V}{\Delta \vdash T \le V} \qquad \text{S3-OBJECT}\ \Delta \vdash T \le \texttt{Object} \qquad \text{S3-EXTENDS}\ \frac{X\,\texttt{extends}\,T \in \Delta}{\Delta \vdash X \le T}$$

$$\text{S3-SUPER}\ \frac{X\,\texttt{super}\,T \in \Delta}{\Delta \vdash T \le X} \qquad \text{S3-OPEN}\ \frac{\Delta, \overline{P} \vdash N \le T \quad \overline{X} \cap \mathsf{ftv}(\Delta, T) = \emptyset}{\Delta \vdash \exists \overline{X}\,\texttt{where}\,\overline{P}\,.\,N \le T} \qquad \text{S3-ABSTRACT}\ \frac{T = [\overline{U/X}]N \quad (\forall i)\ \Delta \Vdash [\overline{U/X}]P_i}{\Delta \vdash T \le \exists \overline{X}\,\texttt{where}\,\overline{P}\,.\,N}$$

Fig. 4. Syntax, entailment, and subtyping for $\mathcal{EX}_{uplo}$.

4 Subtyping Existential Types with Upper and Lower Bounds

This section considers the calculus $\mathcal{EX}_{uplo}$, which is similar in spirit to $\mathcal{EX}_{impl}$, but supports upper and lower bounds (*uplo*) for type variables but no implementation constraints. Other researchers [3, 4, 20] use formal systems very similar to $\mathcal{EX}_{uplo}$ for modeling Java wildcards [21]. It is not the intention of $\mathcal{EX}_{uplo}$ to provide another formalization of wildcards, but rather to expose the essential ingredients that make subtyping undecidable in a calculus as simple as possible. Scala [13] as well as the initial design of the full JavaGI language employ existential types with upper and lower bounds as a replacement for Java wildcards.

4.1 Definition of $\mathcal{EX}_{uplo}$

Fig. 4 defines the syntax and the entailment and subtyping relations of $\mathcal{EX}_{uplo}$. A class type N is either `Object` or an instantiated generic class $C\texttt{<}\overline{X}\texttt{>}$, where the type arguments must be type variables. A type T is a type variable, a class type, or an existential. Unlike in $\mathcal{EX}_{impl}$, existentials in $\mathcal{EX}_{uplo}$ may quantify over several type variables, they support multiple constraints, and the body of an existential must be a class type. A constraint P places either an upper bound ($X\,\texttt{extends}\,T$) or a lower bound ($X\,\texttt{super}\,T$) on a type variable X. Type environments Δ are finite set of constraints P with Δ, P standing for $\Delta \cup \{P\}$.

Class definitions and inheritance are omitted from $\mathcal{EX}_{uplo}$. The only assumption is that every class name C comes with a fixed arity that is respected when applying C to type arguments. There are some further (implicit) restrictions:

Syntax

$$\begin{array}{rcl} \tau^+ & ::= & \mathsf{Top} \mid \forall \alpha_0 \leq \tau_0^- \ldots \alpha_n \leq \tau_n^- \,.\, \neg\, \tau^- \\ \tau^- & ::= & \alpha \mid \forall \alpha_0 \ldots \alpha_n \,.\, \neg\, \tau^+ \\ \Gamma^- & ::= & \emptyset \mid \Gamma^-, \alpha \leq \tau^- \end{array}$$

$\Gamma^- \vdash \sigma^- \leq \tau^+$

$$\text{D-TOP}\quad \Gamma \vdash \tau \leq \mathsf{Top} \qquad \text{D-VAR}\quad \frac{\tau \neq \mathsf{Top} \quad \Gamma \vdash \Gamma(\alpha) \leq \tau}{\Gamma \vdash \alpha \leq \tau} \qquad \text{D-ALL-NEG}\quad \frac{\Gamma, \alpha_0 \leq \phi_0 \ldots \alpha_n \leq \phi_n \vdash \tau \leq \sigma}{\Gamma \vdash \forall \alpha_0 \ldots \alpha_n \,.\, \neg\, \sigma \leq \forall \alpha_0 \leq \phi_0 \ldots \alpha_n \leq \phi_n \,.\, \neg\, \tau}$$

Fig. 5. Syntax and subtyping for $F^D_{\leq}$.

(1) If $T = \exists \overline{X}\, \mathtt{where}\, \overline{P} \,.\, N$, then $\overline{X} \neq \bullet$ and $\overline{X} \subseteq \mathsf{ftv}(N)$. That is, an existential must abstract over at least one type variable and all its bounded type variables must appear in the body type N.
(2) If $T = \exists \overline{X}\, \mathtt{where}\, \overline{P} \,.\, N$ and $P \in \overline{P}$, then $P = Y\, \mathtt{extends}\, T$ or $P = Y\, \mathtt{super}\, T$ with $Y \in \overline{X}$. That is, only bound variables may be constrained.
(3) A type variable must not have both upper and lower bounds.[7]

These three restrictions simplify the formulation of a variant of $\mathcal{EX}_{uplo}$'s subtyping relation without an explicit rule for transitivity (see Appendix D).

Constraint entailment ($\Delta \Vdash T\, \mathtt{extends}\, U$ and $\Delta \Vdash U\, \mathtt{super}\, T$) uses subtyping ($\Delta \vdash T \leq U$) to check that the constraint given holds. The subtyping rules for $\mathcal{EX}_{uplo}$ are similar to those for $\mathcal{EX}_{impl}$, except that `Object` is now a supertype of every type and that rules S$_3$-EXTENDS and S$_3$-SUPER use assumptions from Δ. Moreover, rule S$_3$-ABSTRACT possibly needs to "guess" some of the types $\overline{U}$ because, unlike in $\mathcal{EX}_{impl}$, existentials in $\mathcal{EX}_{uplo}$ may quantify over more than one type variable.

4.2 Undecidability of Subtyping in $\mathcal{EX}_{uplo}$

To get a feeling how subtyping derivations in $\mathcal{EX}_{uplo}$ may lead to infinite regress, consider the goal $\{X\, \mathtt{extends}\, \neg\, U\} \vdash X \leq \neg\, C\texttt{<}X\texttt{>}$, where $\neg\, T$ is an abbreviation for $\exists X\, \mathtt{where}\, X\, \mathtt{super}\, T \,.\, D\texttt{<}X\texttt{>}$ such that X is fresh. Searching for a derivation of this goal quickly leads to a subgoal of the form $\{X\, \mathtt{extends}\, \neg\, U, Z\, \mathtt{super}\, U\} \vdash X \leq \neg\, C\texttt{<}X\texttt{>}$, where Z is a fresh type variable introduced by rule S$_3$-OPEN. The details are left as an exercise to the reader.

The undecidability proof of subtyping in $\mathcal{EX}_{uplo}$ is by reduction from $F^D_{\leq}$ [14], a restricted version of $F_{\leq}$ [5]. Pierce defines $F^D_{\leq}$ for his undecidability proof of $F_{\leq}$ subtyping [14]. Fig. 5 recapitulates $F^D_{\leq}$'s syntax and subtyping relation. Let n be a fixed natural number. A type τ is either an n-positive type, τ^+, or an n-negative type, τ^-, where n stands for the number of type variables (minus one) bound at the top-level of the type. An n-negative type environment Γ^- associates type

[7] Modeling Java wildcards requires upper and lower bounds for the same type variable in certain situations.

$$
\begin{aligned}
[\![\mathsf{Top}]\!]^+ &= \texttt{Object} \\
[\![\forall \alpha_0 \leq \tau_0^- \ldots \alpha_n \leq \tau_n^- \,.\, \neg\, \tau^-]\!]^+ &= \neg\, \exists Y, \overline{X^{\alpha_i}}\ \texttt{where}\ X^{\alpha_0}\ \texttt{extends}\ [\![\tau_0]\!]^- \ldots \\
&\qquad X^{\alpha_n}\ \texttt{extends}\ [\![\tau_n]\!]^-, Y\ \texttt{extends}\ [\![\tau]\!]^- \\
&\qquad .\, C^{n+2}\texttt{<}Y, \overline{X^{\alpha_i}}\texttt{>} \\
[\![\alpha]\!]^- &= X^\alpha \\
[\![\forall \alpha_0 \ldots \alpha_n \,.\, \neg\, \tau^+]\!]^- &= \neg\, \exists Y, \overline{X^{\alpha_i}}\ \texttt{where}\ Y\ \texttt{extends}\ [\![\tau]\!]^+ \,.\, C^{n+2}\texttt{<}Y, \overline{X^{\alpha_i}}\texttt{>} \\
[\![\emptyset]\!]^- &= \emptyset \\
[\![\Gamma, \alpha \leq \tau^-]\!]^- &= [\![\Gamma]\!]^-, X^\alpha\ \texttt{extends}\ [\![\tau]\!]^- \\
[\![\Gamma^- \vdash \tau^- \leq \sigma^+]\!] &= [\![\Gamma]\!]^- \vdash [\![\tau]\!]^- \leq [\![\sigma]\!]^+
\end{aligned}
$$

Fig. 6. Reduction from $F^D_{\leq}$ to $\mathcal{EX}_{uplo}$.

variables α with upper bounds τ^-. The polarity ($+$ or $-$) characterizes at which positions of a subtyping judgment a type or type environment may appear. For readability, the polarity is often omitted and n is left implicit.

An *n-ary subtyping judgment* in $F^D_{\leq}$ has the form $\Gamma^- \vdash \sigma^- \leq \tau^+$, where Γ^- is an n-negative type environment, σ^- is an n-negative type, and τ^+ is an n-positive type. Only n-negative types appear to the left and only n-positive types appear to the right of the $\leq$ symbol. The subtyping rule D-ALL-NEG compares two quantified types $\sigma = \forall \alpha_0 \ldots \alpha_n \,.\, \neg\, \sigma'$ and $\tau = \forall \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \alpha_n \,.\, \neg\, \tau'$ by swapping the left- and right-hand sides of the subtyping judgment and checking $\tau' \leq \sigma'$ under the extended environment $\Gamma, \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \tau_n$. The rule is correct with respect to $F_{\leq}$ because we may interpret every $F^D_{\leq}$ type as an $F_{\leq}$ type:

$$
\begin{aligned}
\forall \alpha_0 \ldots \alpha_n \,.\, \neg\, \sigma' &\equiv \forall \alpha_0 \leq \mathsf{Top} \ldots \forall \alpha_n \leq \mathsf{Top}. \forall \beta \leq \sigma' \,.\, \beta \quad (\beta \text{ fresh}) \\
\forall \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \alpha_n \,.\, \neg\, \tau' &\equiv \forall \alpha_0 \leq \tau_0 \ldots \forall \alpha_n \leq \tau_n. \forall \beta \leq \tau' \,.\, \beta \qquad (\beta \text{ fresh})
\end{aligned}
$$

Using these abbreviations, every $F^D_{\leq}$ subtyping judgment can be read as an $F_{\leq}$ subtyping judgment. The subtyping relations in $F^D_{\leq}$ and $F_{\leq}$ coincide for judgments in their common domain [14].

It is sufficient to consider only *closed judgments*. A type τ is closed under Γ if $\mathsf{ftv}(\tau) \subseteq \mathsf{dom}(\Gamma)$ (where $\mathsf{dom}(\alpha_1 \leq \tau_1, \ldots, \alpha_n \leq \tau_n) = \{\alpha_1, \ldots, \alpha_n\}$) and, if $\tau = \forall \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \tau_n \,.\, \neg\, \sigma$, then no α_i appears free in any τ_j. A type environment Γ is closed if $\Gamma = \emptyset$ or $\Gamma = \Gamma', \alpha \leq \tau$ with Γ' closed and τ closed under Γ'. A judgment $\Gamma \vdash \tau \leq \sigma$ is closed if Γ is closed and τ, σ are closed under Γ.

These notions are sufficient to state the central theorem of this section and sketch its proof.

Theorem 9. *Subtyping in $\mathcal{EX}_{uplo}$ is undecidable.*

Proof. The proof is by reduction from $F^D_{\leq}$. Fig. 6 defines a translation from $F^D_{\leq}$ types, type environments, and subtyping judgments to their corresponding $\mathcal{EX}_{uplo}$ forms. The translation of an n-ary subtyping judgment assumes the existence of two $\mathcal{EX}_{uplo}$ classes: C^{n+2} accepts $n+2$ type arguments, and D^1

takes one type argument. The superscripts in $[\![\cdot]\!]^+$ and $[\![\cdot]\!]^-$ indicate whether the translation acts on positive or negative entities.

As before, a negated type, written $\neg T$, is an abbreviation for an existential with a single `super` constraint: $\neg T \equiv \exists X \,\texttt{where}\, X \,\texttt{super}\, T \,.\, D^1\texttt{<}X\texttt{>}$, where X is fresh. The `super` constraint simulates the behavior of the $F^D_{\leq}$ subtyping rule D-ALL-NEG, which swaps the left- and right-hand sides of subtyping judgments.

An n-positive type $\forall \alpha_0 \leq \tau_0^- \ldots \alpha_n \leq \tau_n^- \,.\, \neg\, \tau^-$ is translated into a negated existential. The existentially quantified type variables $X^{\alpha_0}, \ldots, X^{\alpha_n}$ correspond to the universally quantified type variables $\alpha_0, \ldots, \alpha_n$. The bound $[\![\tau]\!]^-$ of the fresh type variable Y represents the body $\neg\, \tau^-$ of the original type. We cannot use $[\![\tau]\!]^-$ directly as the body because existentials in $\mathcal{EX}_{uplo}$ have only class types as their bodies. The translation for n-negative types is similar to the one for n-positive types. It is easy to see that the $\mathcal{EX}_{uplo}$ types in the image of the translation meet the restrictions defined in Sec. 4.1. Type environments and subtyping judgments are translated in the obvious way.

We now need to verify that $\Gamma \vdash \tau \leq \sigma$ is derivable in $F^D_{\leq}$ if and only if $[\![\Gamma \vdash \tau \leq \sigma]\!]$ is derivable in $\mathcal{EX}_{uplo}$. The "$\Rightarrow$" direction is an easy induction on the derivation of $\Gamma \vdash \tau \leq \sigma$. The "$\Leftarrow$" direction requires more work because the transitivity rule S_3-TRANS (Fig. 4) involves an intermediate type which is not necessarily in the image of the translation. Hence, a direct proof by induction on the derivation of $[\![\Gamma \vdash \tau \leq \sigma]\!]$ fails. To solve this problem, we give an equivalent definition of the $\mathcal{EX}_{uplo}$ subtyping relation that does not include an explicit transitivity rule. See Appendix D for details and the full proof. □

5 Lessons Learned

What are the consequences of this investigation for the design of JavaGI? While bounded existential types are powerful and unify several diverse concepts, they complicate the metatheory of JavaGI's initial design considerably. Also, subtyping with existential types is undecidable in the general case, as demonstrated in the two preceding sections.

There are three alternatives for dealing with this problem: (1) Accept that the subtyping relation is undecidable. (2) Restrict existentials such that subtyping becomes decidable. (3) Remove existentials from JavaGI altogether.

The first alternative (opted for by the Scala compiler) is pragmatic and readily implementable by imposing a resource limit on the subtype checker to avoid divergence. Consequently, the subtyping algorithm would become incomplete with respect to its specification.

The second alternative turns out not to be viable. It is feasible to come up with a set of restrictions that keep the subtyping relation defined in Sec. 3 decidable. (Sec. 3.3 investigated such restrictions for plain interface types.) For the subtyping relation defined in Sec. 4, however, we were not able to identify sensible restrictions without giving up either lower or upper bounds (which are essential for encoding Java wildcards). Moreover, restricting existential types so that subtyping becomes decidable would make an already complex type system

even more complicated. In addition, such restrictions tend to be difficult to communicate to users of the language.

The third alternative comes with the realization that existentials may not be worth the trouble. JavaGI's main contribution is its very general and powerful interface concept (which this paper does not explore, but see [23, 25]). While existential types are related to this concept, they are not at the heart of it. In fact, we conducted several real-world case studies using our implementation of JavaGI without a need for full-blown existential types arising [25].

Under these circumstances, it appears that the price of having bounded existential types at the core of JavaGI is too high. Hence, the current, revised version of JavaGI elides bounded existential types because of their poor power/cost ratio but retains all other features of the previous design. Thus, it gives up some of the power in favor of simplicity.

Several already existing features make up for the lack of existentials. More specifically, the revised design copes with most uses of existentials from Sec. 1: parametric polymorphism in combination with multiple subtyping constraints (as already present in Java) allows to emulate the composition of interface types in most situations; direct support for wildcards avoids their encoding through existential types;[8] JavaGI's `implements` constraints in combination with parametric polymorphism allow the specification of meaningful types for interfaces over families of types.

Even the revised design has to accept compromises to avoid undecidability. Sec. 3.3 reveals that subtyping remains undecidable even if plain interface types replace existentials. The real culprit for undecidability is the ability to provide implementation definitions with interface types acting as implementing types.

Disallowing such implementation definitions completely is a rather severe restriction because it prevents useful implementation definitions such as the one given for `List<X>` in Sec. 2.2. Instead, the revised design allows interfaces as implementing types but it imposes the equivalent of Restriction 3 from Sec. 3.3: if an interface is used as an implementing type then no retroactive implementation can be provided for this interface.[9]

Sometimes, even this restriction is too strict. For example, the use of `List<X>` as an implementing type in Sec. 2.2 prevents retroactive implementations of the `List` interface. *Abstract implementation definitions* are a potential cure. They look similar to non-abstract implementation definitions but do not contribute to constraint entailment and subtyping, so the restriction just explained does not apply. The details of abstract implementation definitions are explained elsewhere [25].

[8] It is an open question whether subtyping for Java wildcards is decidable (see Sec. 6 for details). Of course, the inclusion of wildcards in JavaGI is a concession to ensure backwards compatibility with Java 1.5. An embedding of JavaGI's generalized interface concept in other languages such as C# could easily drop support for wildcards. Thus, the decidability question for wildcards is not intrinsic to decidability of subtyping in JavaGI.

[9] Restriction 2 is more flexible then Restriction 3 but the latter simplifies the detection of ambiguities arising through conflicting implementation definitions and it allows for an efficient implementation of dynamic method lookup.

6 Related Work

Kennedy and Pierce [9] investigate undecidability of subtyping under multiple instantiation inheritance and declaration-site variance. They prove that the general case is undecidable and present three decidable fragments. The proof in Sec. 3 is similar to theirs, although undecidability has different causes: Kennedy and Pierce's system is undecidable because of contravariant generic types, expansive class tables, and multiple instantiation inheritance, whereas undecidability of our system is due to implementation definitions for existentials (or interface types), which cause cyclic interface and multiple instantiation subtyping.

Pierce [14] proves undecidability of subtyping in $F_{\leq}$ by a chain of reductions from the halting problem for two-counter Turing machines. An intermediate link in this chain is the subtyping relation of $F_{\leq}^{D}$, which is also undecidable. Our proof in Sec. 4 works by reduction from $F_{\leq}^{D}$ and is inspired by a reduction given by Ghelli and Pierce [6], who study bounded existential types in the context of $F_{\leq}$ and show undecidability of subtyping. Crucial to the undecidability proof of $F_{\leq}^{\bar{D}}$ is rule D-ALL-NEG: it extends the typing context and essentially swaps the sides of a subtyping judgment. In $\mathcal{EX}_{uplo}$, rule S$_3$-OPEN and rule S$_3$-ABSTRACT together with lower bounds on type variables play a similar role.

Torgersen and coworkers [20] present WildFJ as a model for Java wildcards using existential types. The authors do not prove WildFJ sound. Cameron and coworkers [4] define a similar calculus $\exists$J and prove soundness. However, $\exists$J is not a full model for Java wildcards because it does not support lower bounds for type variables. The same authors present with TameFJ [3] a sound calculus supporting all essential features of Java wildcards. WildFJ's and TameFJ's subtyping rules are similar to the ones of $\mathcal{EX}_{uplo}$ defined in Sec. 4, so the conjecture is that subtyping in WildFJ and TameFJ is also undecidable. The rule XS-ENV of TameFJ is roughly equivalent to the rules S$_3$-OPEN and S$_3$-ABSTRACT of $\mathcal{EX}_{uplo}$.

Decidability of subtyping for Java wildcards is still an open question [11]. One step in the right direction might be the work of Plümicke, who solves the problem of finding a substitution s such that $sT \leq sU$ for Java types T, U with wildcards [16, 17]. Our undecidability result for $\mathcal{EX}_{uplo}$ does not imply undecidability for Java subtyping with wildcards. The proof of this claim would require a translation from subtyping derivations in $\mathcal{EX}_{uplo}$ to subtyping derivations in Java with wildcards, which is not addressed in this paper. In general, existentials in $\mathcal{EX}_{uplo}$ are strictly more powerful than Java wildcards. For example, the existential $\exists X.C\texttt{<}X, X\texttt{>}$ cannot be encoded as the wildcard type $C\texttt{<?, ?>}$ because the two occurrences of `?` denote two distinct types.

The programming language Scala [13] supports existential types in its latest release to provide better interoperability with Java libraries using wildcards and to address the avoidance problem [15, Chapter 8]. The subtyping rules for existentials (Sec. 3.2.10 and Sec. 3.5.2 of the specification [13]) are very similar to the ones for $\mathcal{EX}_{uplo}$. This raises the question whether Scala's subtyping relation with existentials is decidable.

A recent article [25] reports on practical experience with the revised design of JavaGI. It discusses several case studies and describes the implementation

of a compiler and a runtime system for JavaGI, which employs the restrictions discussed in Sec. 5.

7 Conclusion

The paper investigated decidability of subtyping with bounded existential types in the context of JavaGI, Java wildcards, and Scala. It defined two calculi $\mathcal{EX}_{impl}$ and $\mathcal{EX}_{uplo}$ featuring bounded existential types in two variations and proved undecidability of subtyping for both calculi. Subtyping is also undecidable for $\mathcal{IT}_{impl}$, a simplified version of $\mathcal{EX}_{impl}$ without existentials. The paper also suggested a revised version of JavaGI that avoids fully general existentials without giving up much expressivity. The revised version of JavaGI is available at `http://www.informatik.uni-freiburg.de/~wehr/javagi/`.

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A Lemmas for the Proof of Theorem 2

This section establishes some lemmas required to prove Theorem 2. We start with a lemma proving basic properties of our encoding scheme for words over Σ:

Lemma 10. *Suppose $u, v \in \Sigma^*$ and T is a type.*

(i) $[\![u]\!] = [\![v]\!]$ *if, and only if,* $u = v$
(ii) $u \# (v \# T) = uv \# T$
(iii) $u \# [\![v]\!] = [\![uv]\!]$

Proof. Straightforward. □

The next lemma ensures that the types occurring in a derivation of $\Theta_{\mathcal{P}}; \emptyset \vdash \mathtt{S<}[\![u_i]\!], [\![v_i]\!]\mathtt{>} \leq \mathtt{G}$ are of a certain form. ($\Theta_{\mathcal{P}}$ is the program consisting of the interfaces and implementations defined in the proof of Theorem 2.) We use the notation $[n]$ to denote the set $\{1, \ldots, n\}$. Furthermore, $\mathfrak{I}$ and $\mathfrak{J}$ range over (possible empty) sequences of indices drawn from $[n]$, and $\mathfrak{I}\mathfrak{J}$ is the concatenation of $\mathfrak{I}$ and $\mathfrak{J}$. For $\mathfrak{I} = i_1 \ldots i_r$, we write $u_{\mathfrak{I}}$ to denote the word $u_{i_1} \ldots u_{i_r}$.

Lemma 11. *Suppose $\Theta_{\mathcal{P}}; \Delta \vdash T \leq W$. Let U and V be types such that $\mathsf{ftv}(U, V) = \emptyset$ and neither $\mathtt{S}$ nor $\mathtt{G}$ occur in U or V. Assume that either*

$$T = \exists X\, \mathtt{where}\, X\, \mathtt{implements}\, \mathtt{S<}U, V\mathtt{>}\, .\, X, \text{ or}$$
$$T = \exists X\, \mathtt{where}\, X\, \mathtt{implements}\, \mathtt{G}\, .\, X, \text{ or}$$
$$T = Z \text{ for some } Z \text{ with } Z \notin \mathsf{ftv}(W).$$

Moreover, assume that for all $Y\ \mathtt{implements}\ I\mathtt{<}\overline{W'}\mathtt{>} \in \Delta$ either $I\mathtt{<}\overline{W'}\mathtt{>} = \mathtt{G}$ or $I\mathtt{<}\overline{W'}\mathtt{>} = \mathtt{S<}U, V\mathtt{>}$.

(i) Then $W = \exists X\, \mathtt{where}\, P\, .\, X$ and one of the following holds:
  (a) $P = X\ \mathtt{implements}\ \mathtt{S<}U, V\mathtt{>}$.
  (b) $P = X\ \mathtt{implements}\ \mathtt{S<}u_{\mathfrak{I}} \# U, v_{\mathfrak{I}} \# V\mathtt{>}$ *for a non-empty sequence* $\mathfrak{I}$.
  (c) $P = X\ \mathtt{implements}\ \mathtt{G}$.

(ii) If we additionally assume that $W = \exists X\, \mathtt{where}\, X\, \mathtt{implements}\, \mathtt{G}\, .\, X$ then one of the following holds:
  (a) $T = \exists X\, \mathtt{where}\, X\, \mathtt{implements}\, \mathtt{G}\, .\, X$.
  (b) $U = V$ *or* $u_{\mathfrak{I}} \# U = v_{\mathfrak{I}} \# V$ *for non-empty sequence* $\mathfrak{I}$.
  (c) $Y\ \mathtt{implements}\ \mathtt{G} \in \Delta$ *for some* Y.

Proof. Both claims are proved by induction on the derivation of $\Theta_{\mathcal{P}}; \Delta \vdash T \leq W$.

(i) *Case distinction* on the last rule used.
  – *Case* rule S1-REFL: Then $T = W$. The case $T = Z$ for some Z is not possible because we would then also have that $Z \in \mathsf{ftv}(W)$. For the other cases, the claim follows trivially.

– *Case* rule S_1-TRANS: Then

$$\frac{\Theta_{\mathcal{P}}; \Delta \vdash T \leq V \qquad \Theta_{\mathcal{P}}; \Delta \vdash V \leq W}{\Theta_{\mathcal{P}}; \Delta \vdash T \leq W}$$

Applying the I.H. to $\Theta_{\mathcal{P}}; \Delta \vdash T \leq V$ gives us $V = \exists Y\, \texttt{where}\, Q\,.\,Y$ such one of the following holds:
(a) $Q = Y\ \texttt{implements}\ \texttt{S<}U, V\texttt{>}$.
(b) $Q = Y\ \texttt{implements}\ \texttt{S<}u_{\mathfrak{J}} \# U, v \#_{\mathfrak{J}} V\texttt{>}$ for some non-empty sequence $\mathfrak{J}$.
(c) $Q = Y\ \texttt{implements}\ \texttt{G}$.
The claim now follows by applying the I.H. to $\Theta_{\mathcal{P}}; \emptyset \vdash V \leq W$, possibly using Lemma 10(ii).

– *Case* rule S_1-OPEN: Then

$$\frac{\Theta_{\mathcal{P}}; \Delta, Q \vdash Y \leq W \qquad Y \notin \mathsf{ftv}(W)}{\Theta_{\mathcal{P}}; \Delta \vdash \underbrace{\exists Y\, \texttt{where}\, Q\,.\,Y}_{=T} \leq W}$$

and the claim follows by applying the I.H. to $\Theta_{\mathcal{P}}; \Delta, Q \vdash Y \leq T$.

– *Case* rule S_1-ABSTRACT: Then

$$\frac{\Theta_{\mathcal{P}}; \Delta \Vdash [T/X]P}{\Theta_{\mathcal{P}}; \Delta \vdash T \leq \underbrace{\exists X\, \texttt{where}\, P\,.\,X}_{=W}}$$

By the syntax of existentials, we know that $P = X\ \texttt{implements}\ I\texttt{<}\overline{T}\texttt{>}$.
Case distinction on the rule used to derive $\Theta_{\mathcal{P}}, \Delta \Vdash [T/X]P$.

- *Case* rule E_1-LOCAL: Then $[T/X]P \in \Delta$. Hence, either $[T/X]P = T\ \texttt{implements}\ \texttt{G}$ or $[T/X]P = T\ \texttt{implements}\ \texttt{S<}U, V\texttt{>}$. As $\mathsf{ftv}(U, V) = \emptyset$ by assumption, we have either $P = X\ \texttt{implements}\ \texttt{G}$ or $P = X\ \texttt{implements}\ \texttt{S<}U, V\texttt{>}$ as required.
- *Case* rule E_1-IMPL: There are two possibilities:
  * $\texttt{implementation<}X, Y\texttt{>}\ \texttt{S<}u_j \# X, v_j \# Y\texttt{>}\ \texttt{[S<}X, Y\texttt{>]} \in \Theta_{\mathcal{P}}$ and $[T/X]P = \texttt{S<}U', V'\texttt{>}\ \texttt{implements}\ \texttt{S<}u_j \# U', v \#_j V'\texttt{>}$. Then $T = \texttt{S<}U', V'\texttt{>}$, so $U' = U$ and $V' = V$. With $\mathsf{ftv}(U, V) = \emptyset$ also $P = X\ \texttt{implements}\ \texttt{S<}u_j \# U, v_j \# V\texttt{>}$ as required.
  * $\texttt{implementation<}X\texttt{>}\ \texttt{G}\ \texttt{[S<}X, X\texttt{>]} \in \Theta_{\mathcal{P}}$ and $[T/X]P = \texttt{S<}U', V'\texttt{>}\ \texttt{implements}\ \texttt{G}$. But then also $P = X\ \texttt{implements}\ \texttt{G}$.

End case distinction on the rule used to derive $\Theta_{\mathcal{P}}, \Delta \Vdash [T/X]P$.

End case distinction on the last rule used.

(ii) *Case distinction* on the last rule used.

– *Case* rule S_1-REFL: Trivial.

– *Case* rule S_1-TRANS: Then

$$\frac{\Theta_{\mathcal{P}}; \Delta \vdash T \leq V \qquad \Theta_{\mathcal{P}}; \Delta \vdash V \leq W}{\Theta_{\mathcal{P}}; \Delta \vdash T \leq W}$$

We now apply part (i) of this lemma to $\Theta_{\mathcal{P}}; \Delta \vdash T \leq V$ and get that $V = \exists Y\, \texttt{where}\, Q\,.\, Y$ such that for Q either (a), (b), or (c) as in case S_1-TRANS of the proof for part (i) holds. We now can apply the I.H. of the current part of the proof to $\Theta_{\mathcal{P}}; \Delta \vdash V \leq W$ and get that one of the following holds:

(a) $V = \exists Y\, \texttt{where}\, Y\, \texttt{implements}\, \texttt{G}\,.\, Y$. Then the claim follows by applying the I.H. to $\Theta_{\mathcal{P}}; \Delta \vdash T \leq V$.
(b) Either $U = V$ or, with Lemma 10(ii), $u_{\mathfrak{J}'} \,\#\, U = v'_{\mathfrak{J}} \,\#\, V$ for some non-empty sequence $\mathfrak{J}'$. But this is exactly what we need to prove.
(c) $Y\, \texttt{implements}\, \texttt{G} \in \Delta$ for some Y. The claim then holds trivially.

– *Case* rule S_1-OPEN: Then

$$\frac{\Theta_{\mathcal{P}}; \Delta, Q \vdash Y \leq W \qquad Y \notin \mathsf{ftv}(W)}{\Theta_{\mathcal{P}}; \Delta \vdash \underbrace{\exists Y\, \texttt{where}\, Q\,.\, Y}_{=T} \leq W}$$

and the claim follows by applying the I.H. to $\Theta_{\mathcal{P}}; \Delta, Q \vdash Y \leq T$.

– *Case* rule S_1-ABSTRACT: Then

$$\frac{\Theta_{\mathcal{P}}; \Delta \Vdash [T/X]P}{\Theta_{\mathcal{P}}; \Delta \vdash T \leq \underbrace{\exists X\, \texttt{where}\, P\,.\, X}_{=W}}$$

We have $X\, \texttt{implements}\, \texttt{G} = P$ so

$$\Theta_{\mathcal{P}}; \Delta \Vdash T\, \texttt{implements}\, \texttt{G}$$

Case distinction on the rule used to derive $\Theta_{\mathcal{P}}, \Delta \Vdash T\, \texttt{implements}\, \texttt{G}$.

- *Case* rule E_1-LOCAL: Then $T\, \texttt{implements}\, \texttt{G} \in \Delta$. Hence, $T = Z$ and the claim holds.
- *Case* rule E_1-IMPL: Then implementation definition (1) must have been used in the premise of the rule. Hence, $T = \texttt{S<}U', U'\texttt{>}$, so $U = V$ as required.

End case distinction on the rule used to derive $\Theta_{\mathcal{P}}, \Delta \Vdash T\, \texttt{implements}\, \texttt{G}$.

End case distinction on the last rule used. □

Finally, we prove a lemma which directly implies Theorem 2.

Lemma 12. *The PCP instance $\mathcal{P} = \{(u_1, v_1), \ldots, (u_n, v_n)\}$ has a solution if and only if there exists $i \in \{1, \ldots, n\}$ such that $\Theta_{\mathcal{P}}; \emptyset \vdash \texttt{S<}[\![u_i]\!], [\![v_i]\!]\texttt{>} \leq \texttt{G}$ is derivable.*

Proof. We prove the two implications separately.

"⇒": We first show for any non-empty sequence of indices $i_1 \dots i_k$ that

$$\Theta_{\mathcal{P}}; \emptyset \vdash \mathtt{S<}[\![u_{i_k}]\!], [\![v_{i_k}]\!]\mathtt{>} \leq \mathtt{S<}[\![u_{i_1} \dots u_{i_k}]\!], [\![v_{i_1} \dots v_{i_k}]\!]\mathtt{>} \tag{3}$$

The proof is by induction on k. The base case follows from reflexivity of subtyping. For the inductive step, the induction hypothesis yields

$$\Theta_{\mathcal{P}}; \emptyset \vdash \mathtt{S<}[\![u_{i_{k+1}}]\!], [\![v_{i_{k+1}}]\!]\mathtt{>} \leq T \tag{4}$$

where $T = \mathtt{S<}[\![u_{i_2} \dots u_{i_{k+1}}]\!], [\![v_{i_2} \dots v_{i_{k+1}}]\!]\mathtt{>}$. Choosing a suitable implementation definition from (1), we get

$$\Theta_{\mathcal{P}}; \emptyset \Vdash T \,\mathtt{implements}\, \mathtt{S<}u_{i_1} \# [\![u_{i_2} \dots u_{i_{k+1}}]\!], v_{i_1} \# [\![v_{i_2} \dots v_{i_{k+1}}]\!]\mathtt{>}$$

Hence, by Lemma 10(iii) and rule S1-ABSTRACT we also have

$$\Theta_{\mathcal{P}}; \emptyset \vdash T \leq \mathtt{S<}[\![u_{i_1} \dots u_{i_{k+1}}]\!], [\![v_{i_1} \dots v_{i_{k+1}}]\!]\mathtt{>}$$

Claim (3) now follows with (4) and transitivity of subtyping.

Now suppose that $\mathfrak{I} = i_1 \dots i_r$ is a solution to $\mathcal{P}$. Then we have from (3)

$$\Theta_{\mathcal{P}}; \emptyset \vdash \mathtt{S<}[\![u_{i_r}]\!], [\![v_{i_r}]\!]\mathtt{>} \leq \mathtt{S<}[\![u_{\mathfrak{I}}]\!], [\![v_{\mathfrak{I}}]\!]\mathtt{>}$$

Because $u_{\mathfrak{I}} = v_{\mathfrak{I}}$ we get $[\![u_{\mathfrak{I}}]\!] = [\![v_{\mathfrak{I}}]\!]$ by Lemma 10(i), so implementation definition (1) yields

$$\Theta_{\mathcal{P}}; \emptyset \Vdash \mathtt{S<}[\![u_{\mathfrak{I}}]\!], [\![v_{\mathfrak{I}}]\!]\mathtt{>}\, \mathtt{implements}\, \mathtt{G}$$

Applying rules S1-ABSTRACT and S1-TRANS gives us $\Theta_{\mathcal{P}}; \emptyset \vdash \mathtt{S<}[\![u_{i_r}]\!], [\![v_{i_r}]\!]\mathtt{>} \leq \mathtt{G}$, as required.

"⇐": Given that $\Theta_{\mathcal{P}}; \emptyset \vdash \mathtt{S<}[\![u_i]\!], [\![v_i]\!]\mathtt{>} \leq \mathtt{G}$ is derivable for some $i \in \{1, \dots, n\}$, we get from Lemma 11(ii) that either $[\![u_i]\!] = [\![v_i]\!]$ or that there exists a non-empty sequence $\mathfrak{I}$ such that $u_{\mathfrak{I}} \# [\![u_i]\!] = v_{\mathfrak{I}} \# [\![v_i]\!]$. For the first case, we have $u_i = v_i$ by Lemma 10(i); for the second case, we get $[\![u_{\mathfrak{I}} u_i]\!] = [\![v_{\mathfrak{I}} v_i]\!]$ by Lemma 10(iii), and $u_{\mathfrak{I}} u_i = v_{\mathfrak{I}} v_i$ by Lemma 10(i). Hence, $\mathcal{P}$ has a solution. □

B Proof of Theorem 5

Fig. 7 defines the relation $\Phi \vdash' T \leq U$, a variant of the subtyping relation of $\mathcal{IT}_{impl}$ without a built-in transitivity rule. We first verify that $\Phi \vdash T \leq U$ and $\Phi \vdash' T \leq U$ are equivalent.

Lemma 13. *If $\Phi \vdash' T \leq U$ then $\Phi \vdash T \leq U$.*

Proof. Straightforward induction on the derivation of $\Phi \vdash' T \leq U$.

$\boxed{\Phi \vdash' T \leq T}$

$$\text{S}_2\text{-REFL'}\quad \Phi \vdash' T \leq T \qquad \text{S}_2\text{-IMPL'}\quad \frac{(\forall \overline{X}.\, T \leq U) \in \Phi \qquad W \neq [\overline{V/X}]T \qquad \Phi \vdash' [\overline{V/X}]U \leq W}{\Phi \vdash' [\overline{V/X}]T \leq W}$$

Fig. 7. Subtyping for $\mathcal{IT}_{impl}$ without transitivity rule.

$\boxed{\Phi; \mathcal{G} \vdash_{\text{a}} T \leq T}$

$$\text{S}_2\text{-ALG-REFL}\quad \Phi; \mathcal{G} \vdash_{\text{a}} T \leq T \qquad \text{S}_2\text{-ALG-IMPL}\quad \frac{(\forall \overline{X}.\, T \leq U) \in \Phi \qquad [\overline{V/X}]U \notin \mathcal{G} \qquad W \neq [\overline{V/X}]T \qquad \Phi; \mathcal{G} \cup \{[\overline{V/X}]U\} \vdash_{\text{a}} [\overline{V/X}]U \leq W}{\Phi; \mathcal{G} \vdash_{\text{a}} [\overline{V/X}]T \leq W}$$

$\boxed{\Phi \vdash_{\text{a}} T \leq T}$

$$\text{S}_2\text{-ALG-SUB}\quad \frac{\Phi; \{T\} \vdash_{\text{a}} T \leq U}{\Phi \vdash_{\text{a}} T \leq U}$$

Fig. 8. Algorithmic subtyping for $\mathcal{IT}_{impl}$.

Lemma 14. *If $\Phi \vdash' T \leq U$ and $\Phi \vdash' U \leq V$ then $\Phi \vdash' T \leq V$*

Proof. Follows by induction on the derivation of $\Phi \vdash' T \leq U$.

Lemma 15. *If $\Phi \vdash T \leq U$ then $\Phi \vdash' T \leq U$.*

Proof. Follows by case distinction on the last rule in the derivation of $\Phi \vdash T \leq U$, using Lemma 14 if this rule is S$_2$-TRANS.

Fig. 8 defines the algorithmic subtyping relation $\Phi \vdash_{\text{a}} T \leq U$ for $\mathcal{IT}_{impl}$. The auxiliary relation $\Phi; \mathcal{G} \vdash_{\text{a}} T \leq U$ uses a set of types $\mathcal{G}$ to prevent recursive invocations on a goal that was already visited before.

Lemma 16. *If $\Phi \vdash_{\text{a}} T \leq U$ then $\Phi \vdash' T \leq U$.*

Proof. A straightforward rule induction shows that $\Phi; \mathcal{G} \vdash_{\text{a}} T \leq U$ implies $\Phi \vdash' T \leq U$ for any $\mathcal{G}$. Inverting $\Phi \vdash_{\text{a}} T \leq U$ yields $\Phi; \{T\} \vdash_{\text{a}} T \leq U$, so the claim holds.

Lemma 17. *If $\Phi \vdash' T \leq U$ then $\Phi \vdash_{\text{a}} T \leq U$.*

Proof. Let $\mathcal{D}_1$ be the derivation of $\Phi \vdash' T \leq U$ and let $\mathcal{D}_2$ be the immediate subderivation of $\mathcal{D}_1$, let $\mathcal{D}_3$ be the immediate subderivation of $\mathcal{D}_2$, and so on. It is easy to verify that all $\mathcal{D}_i$ have the form $\Phi \vdash' T_i \leq U$ for types $T = T_1, \ldots, T_n$. We may safely assume that all types $T_1, \ldots, T_n$ are pairwise disjoint. (Otherwise, there are two derivations with identical conclusions, so we simply replace the larger derivation with the smaller one.) With these considerations in place, a straightforward induction shows that $\Phi \vdash' T \leq U$ implies $\Phi; \{T\} \vdash_{\text{a}} T \leq U$. Thus, we get $\Phi \vdash_{\text{a}} T \leq U$ by rule S$_2$-ALG-SUB.

Proof (of Theorem 5). With Lemmas 13, 15, 16, and 17, it follows that $\Phi \vdash T \leq U$ and $\Phi \vdash_{\mathrm{a}} T \leq U$ are equivalent. Thus, we only need to verify that the algorithm induced by $\Phi \vdash_{\mathrm{a}} T \leq U$ terminates. Suppose that $\Phi; \mathcal{G} \vdash_{\mathrm{a}} T' \leq U'$ is a subderivation in an attempt to prove the original goal $\Phi \vdash_{\mathrm{a}} T \leq U$. A straightforward induction on the number of rule applications needed to reach the subderivation shows that $\mathcal{G} \subseteq \mathcal{S}_{T,\Phi}$. Thus, $|\mathcal{S}_{T,\Phi}| - |\mathcal{G}| \in \mathbb{N}$. Furthermore, rule S$_2$-ALG-IMPL ensures that the measure $|\mathcal{S}_{T,\Phi}| - |\mathcal{G}|$ decreases when moving from the conclusion to the premise. Hence, the algorithm induced by $\Phi \vdash_{\mathrm{a}} T \leq U$ terminates. □

C Proof of Lemma 7 and Lemma 8

Proof (of Lemma 7). Define a graph $G_\Phi = G = (\mathcal{V}, \mathcal{E})$ such that

$$\mathcal{V} = \Phi$$
$$\mathcal{E} = \{(\varphi, \varphi') \in \Phi \times \Phi \mid \text{if } \varphi = \forall \overline{X}.\, I\langle \overline{T} \rangle \leq J\langle \overline{U} \rangle \text{ then } \varphi' = \forall \overline{Y}.\, J\langle \overline{V} \rangle \leq I'\langle \overline{W} \rangle\}$$

G is acyclic because Φ is contractive. Thus, there exists an upper bound $L \in \mathbb{N}$ on the length of any path in G.

In the following, write $T \xrightarrow{\forall \overline{X}.\, T' \leq U'} U$ if, and only if, there exists a substitution $[\overline{V}/\overline{X}]$ with $[\overline{V}/\overline{X}]T' = T$ and $[\overline{V}/\overline{X}]U' = U$. It is straightforward to verify that $U \in \mathcal{S}_{T,\Phi}$ if, and only if, there exists a path $\varphi_1, \ldots, \varphi_n$ in G such that $T \xrightarrow{\varphi_1} \ldots \xrightarrow{\varphi_n} U$.

Define the *size* of types and subtyping schemes as follows:

$$\mathsf{size}(X) = 1$$
$$\mathsf{size}(I\langle \overline{T} \rangle) = 1 + \sum_{i=1}^{n} \mathsf{size}(T_i)$$
$$\mathsf{size}(\forall \overline{X}.\, I\langle \overline{T} \rangle \leq J\langle \overline{U} \rangle) = \mathsf{size}(J\langle \overline{U} \rangle)$$

Then $T \xrightarrow{\varphi} U$ implies $\mathsf{size}(U) \leq \mathsf{size}(\varphi) \cdot \mathsf{size}(T) + \mathsf{size}(\varphi)$. If now $\delta \in \mathbb{N}$ is an upper bound on the size of all $\varphi \in \Phi$, then $T \xrightarrow{\varphi_1} \ldots \xrightarrow{\varphi_n} U$ with $\varphi_1, \ldots, \varphi_n \in \Phi$ implies that $\mathsf{size}(U) \leq \delta^n \cdot \mathsf{size}(T) + \sum_{i=1}^{n} \delta^i$. Thus, $U \in \mathcal{S}_{T,\Phi}$ implies $\mathsf{size}(U) \leq \delta^L \cdot \mathsf{size}(T) + \sum_{i=1}^{L} \delta^i$, so the set $\mathcal{S}_{T,\Phi}$ is finite because there exist only finitely many types with a bounded size. □

Proof (of Lemma 8). Assume that Restriction 4 holds but Restriction 1 does not. Thus, there exists a type $I\langle \overline{T} \rangle$ such that $\mathcal{S}_{I\langle \overline{T} \rangle,\Phi}$ is infinite. Because types are formed from only finitely many interface names, there must exist an interface name J and infinitely many, pairwise disjoint sequences of types $\overline{U}$ such that $J\langle \overline{U} \rangle \in \mathcal{S}_{I\langle \overline{T} \rangle,\Phi}$ for all $\overline{U}$. It is easy to verify that $J\langle \overline{U} \rangle \in \mathcal{S}_{I\langle \overline{T} \rangle,\Phi}$ implies $\Phi \vdash I\langle \overline{T} \rangle \leq J\langle \overline{U} \rangle$, which leads to a contradiction to Restriction 4. □

$$\frac{\Delta \vdash' T \le U}{\Delta \Vdash' T \,\texttt{extends}\, U}\ \text{E}_3\text{-EXTENDS'} \qquad \frac{\Delta \vdash' U \le T}{\Delta \Vdash' T \,\texttt{super}\, U}\ \text{E}_3\text{-SUPER'}$$

$$\frac{T = X \text{ or } T = N}{\Delta \vdash' T \le T}\ \text{S}_3\text{-REFL'} \qquad \Delta \vdash' T \le \texttt{Object}\ \text{S}_3\text{-OBJECT'} \qquad \frac{X \,\texttt{extends}\, T' \in \Delta \qquad \Delta \vdash' T' \le T}{\Delta \vdash' X \le T}\ \text{S}_3\text{-EXTENDS'}$$

$$\frac{X \,\texttt{super}\, T' \in \Delta \qquad \Delta \vdash' T \le T'}{\Delta \vdash' T \le X}\ \text{S}_3\text{-SUPER'} \qquad \frac{\Delta, \overline{P} \vdash' N \le T \qquad \overline{X} \cap \mathsf{ftv}(\Delta, T) = \emptyset}{\Delta \vdash' \exists \overline{X}\, \texttt{where}\, \overline{P}\,.\, N \le T}\ \text{S}_3\text{-OPEN'}$$

$$\frac{N = [\overline{Y/X}]M \qquad (\forall i)\ \Delta \Vdash' [\overline{Y/X}]P_i}{\Delta \vdash' N \le \exists \overline{X}\, \texttt{where}\, \overline{P}\,.\, M}\ \text{S}_3\text{-ABSTRACT'}$$

Fig. 9. Subtyping for $\mathcal{EX}_{uplo}$ without transitivity rule.

D Lemmas for the Proof of Theorem 9

Fig. 9 shows the definition of the alternative subtyping relation $\Delta \vdash' T \le T$ for $\mathcal{EX}_{uplo}$ that does not have a built-in transitivity rule. To establish equivalence with the original subtyping relation (Fig. 4), we first prove that the alternative subtyping relation is reflexive and transitive.

Lemma 18 (Reflexivity). *For all types T, $\Delta \vdash' T \le T$.*

Proof. The only interesting case is $T = \exists \overline{X}\, \texttt{where}\, \overline{P}\,.\, N$. Then we have

$$\text{S}_3\text{-OPEN'}\ \frac{\text{S}_3\text{-ABSTRACT'}\ \dfrac{N = N \qquad (\forall i)\ \Delta, \overline{P} \Vdash' P_i}{\Delta, \overline{P} \vdash' N \le \exists \overline{X}\, \texttt{where}\, \overline{P}\,.\, N} \qquad \overline{X} \cap \mathsf{ftv}(\Delta, T) = \emptyset}{\Delta \vdash' \exists \overline{X}\, \texttt{where}\, \overline{P}\,.\, N \le \exists \overline{X}\, \texttt{where}\, \overline{P}\,.\, N}$$

Note that it is easy to verify that $\Delta \Vdash' P$ for any $P \in \Delta$. □

Lemma 19 (Transitivity). *If $\Delta \vdash' T \le U$ and $\Delta \vdash' U \le V$, then $\Delta \vdash' T \le V$.*

The prove of the transitivity lemma makes essential use of the fact that type variables do not have both lower and upper bounds and that only type variables may occur as type arguments of generic classes.

Proof. We define the *size* of a type or constraint as follows:

$$\begin{aligned}
\mathsf{size}(X) &= 1 \\
\mathsf{size}(C\texttt{<}\overline{T}\texttt{>}) &= 1 + \mathsf{size}(\overline{T}) \\
\mathsf{size}(\texttt{Object}) &= 1 \\
\mathsf{size}(\exists \overline{X}\, \texttt{where}\, \overline{P}\,.\, N) &= 1 + \mathsf{size}(\overline{P}) + \mathsf{size}(N) \\
\mathsf{size}(X \,\texttt{extends}\, T) &= \mathsf{size}(T) \\
\mathsf{size}(X \,\texttt{super}\, T) &= \mathsf{size}(T)
\end{aligned}$$

We use the notation $\mathsf{size}(\overline{\xi})$ as an abbreviation for $\sum_i \mathsf{size}(\xi_i)$.

Moreover, we define the *domain* of a type environment Δ as $\mathsf{dom}(\Delta) = \{X \mid X \,\mathtt{extends}\, T \in \Delta \text{ or } X \,\mathtt{super}\, T \in \Delta\}$, and the *range* of a type environment Δ as $\mathsf{rng}(\Delta) = \{T \mid X \,\mathtt{extends}\, T \in \Delta \text{ or } X \,\mathtt{super}\, T \in \Delta\}$.

We now strengthen the claim as follows:

> *Let* $n \in \mathbb{N}$.
>
> *(i) Assume* $\mathsf{size}(U) = n$. *If* $\Delta \vdash' T \le U$ *and* $\Delta \vdash' U \le V$, *then* $\Delta \vdash' T \le V$.
>
> *(ii) Assume* $\mathsf{size}(\overline{P}) = n$. *If* $\Delta', \overline{P} \vdash' W_1 \le W_2$ *and* $\overline{[Y/X]}\Delta' \Vdash' \overline{[Y/X]}P$ *for all* $P \in \overline{P}$ *and* $\overline{X} \cap \mathsf{dom}(\Delta') = \emptyset$, *then* $[\overline{Y/X}]\Delta' \vdash' [\overline{Y/X}]W_1 \le [\overline{Y/X}]W_2$.

We then prove that claims (i) and (ii) hold for all $n \in \mathbb{N}$ by complete induction. Suppose $n \in \mathbb{N}$ and assume that

$$\text{(i) and (ii) hold for all } n' \in \mathbb{N} \text{ with } n' < n. \tag{5}$$

We now have to prove that (i) and (ii) hold for n.

(i) We prove claim (i) by induction on the combined size of the derivations of $\Delta \vdash' T \le U$ and $\Delta \vdash' U \le V$. We perform a case analysis on the last rules used in these derivations. The following tables lists all possible combinations; the rows contain the last rule used in $\Delta \vdash' T \le U$, the columns the last rule used in $\Delta \vdash' U \le V$.

	S₃-REFL'	S₃-OBJECT'	S₃-EXTENDS'	S₃-SUPER'	S₃-OPEN'	S₃-ABSTRACT'
S₃-REFL'	✓	✓	✓	✓	✓	✓
S₃-OBJECT'	✓	✓	↯	✓	↯	(a)
S₃-EXTENDS'	✓	✓	✓	✓	✓	✓
S₃-SUPER'	✓	✓	(b)	✓	↯	↯
S₃-OPEN'	✓	✓	✓	✓	✓	✓
S₃-ABSTRACT'	✓	✓	↯	✓	(c)	↯

Cases marked with ✓ are trivial or follow directly from the inner induction hypothesis; cases marked with ↯ can never occur because they put conflicting constraints on the form of U. We now deal with the remaining cases.

(a) Then $U = \mathtt{Object}$, $V = \exists \overline{X}\, \mathtt{where}\, \overline{P}\,.\, N$ and the premise of S₃-ABSTRACT' requires $\mathtt{Object} = [\overline{Y/X}]N$, so $N = \mathtt{Object}$. But this contradicts the restriction in restriction (1) on page 10.

(b) Then $U = X$ and Δ contains an lower and upper bound for X. This is a contradiction to restriction (3) on page 10.

(c) Then $T = M$ and $U = \exists \overline{X}\, \mathtt{where}\, \overline{P}\,.\, N$ and

$$\frac{M = [\overline{Y/X}]N \quad (\forall i)\ \Delta \Vdash' [\overline{Y/X}]P_i}{\Delta \vdash' M \le \exists \overline{X}\, \mathtt{where}\, \overline{P}\,.\, N} \qquad \frac{\Delta, \overline{P} \vdash' N \le V \quad \mathsf{ftv}(\Delta, V) \cap \overline{X} = \emptyset}{\Delta \vdash' \exists \overline{X}\, \mathtt{where}\, \overline{P}\,.\, N \le V}$$

We have

$$\mathsf{size}(\overline{P}) < \mathsf{size}(U) = n$$

With (5) we then get

$$[\overline{Y/X}]\Delta \vdash' [\overline{Y/X}]N \leq [\overline{Y/X}]V$$

Because $T = [\overline{Y/X}]N$ and $\overline{X} \cap \mathsf{ftv}(\Delta, V) = \emptyset$, we have

$$\Delta \vdash' T \leq V$$

as required.

(ii) We proceed by induction on the derivation $\mathcal{D}$ of $\Delta', \overline{P} \vdash' W_1 \leq W_2$. We have already proved (i) for n, so with (5)

$$\text{(i) holds for all } n' \in \mathbb{N} \text{ with } n' \leq n \tag{6}$$

Case distinction on the last rule used in $\mathcal{D}$.

- *Case* rule S3-REFL': Follows with Lemma 18.
- *Case* rule S3-OBJECT': Trivial.
- *Case* rule S3-EXTENDS': We then have $W_1 = X$ and

$$\frac{X \,\texttt{extends}\, W_2' \in \Delta', \overline{P} \qquad \Delta', \overline{P} \vdash' W_2' \leq W_2}{\Delta', \overline{P} \vdash' X \leq W_2}$$

  Applying the inner I.H. yields

$$[\overline{Y/X}]\Delta' \vdash' [\overline{Y/X}]W_2' \leq [\overline{Y/X}]W_2 \tag{7}$$

  - If $X \,\texttt{extends}\, W_2' \in \overline{P}$ then

$$[\overline{Y/X}]\Delta' \vdash' [\overline{Y/X}]X \leq [\overline{Y/X}]W_2' \tag{8}$$

    by the assumption. We also have

$$\mathsf{size}([\overline{Y/X}]W_2') = \mathsf{size}(W_2') \leq \mathsf{size}(\overline{P}) = n$$

    Using (6) on (8) and (7) yields

$$[\overline{Y/X}]\Delta' \vdash' [\overline{Y/X}]X \leq [\overline{Y/X}]W_2$$

    as required.
  - If $X \,\texttt{extends}\, W_2' \in \Delta'$ then $[\overline{Y/X}]X = X$ because $\overline{X} \cap \mathsf{dom}(\Delta) = \emptyset$. With (7) and rule S3-EXTENDS', we get the required result.
- *Case* rule S3-SUPER': Follows analogously.

– *Case* rule S$_3$-OPEN': Then $W_1 = \exists\overline{Z}\,\mathtt{where}\,\overline{Q}\,.\,N$ and

$$\frac{\Delta', \overline{P}, \overline{Q} \vdash' N \leq W_2 \qquad \overline{Z} \cap \mathsf{ftv}(\Delta', \overline{P}, W_2) = \emptyset}{\Delta', \overline{P} \vdash' \exists\overline{Z}\,\mathtt{where}\,\overline{Q}\,.\,N \leq W_2}$$

Because the $\overline{Z}$ are sufficiently fresh, we may assume

$$[\overline{Y/X}](\exists\overline{Z}\,\mathtt{where}\,\overline{Q}\,.\,N) = \exists\overline{Z}\,\mathtt{where}\,([\overline{Y/X}]\overline{Q})\,.\,([\overline{Y/X}]N)$$
$$\overline{Z} \cap \mathsf{ftv}([\overline{Y/X}]\Delta, [\overline{Y/X}]W_2) = \emptyset$$

Using the inner I.H. yields

$$[\overline{Y/X}](\Delta', \overline{Q}) \vdash' [\overline{Y/X}]N \leq [\overline{Y/X}]W_2$$

Thus with S$_3$-OPEN'

$$[\overline{Y/X}]\Delta' \vdash' [\overline{Y/X}](\exists\overline{Z}\,\mathtt{where}\,\overline{Q}\,.\,N) \leq [\overline{Y/X}]W_2$$

– *Case* rule S$_3$-ABSTRACT': Then $W_2 = \exists\overline{Z}\,\mathtt{where}\,\overline{Q}\,.\,N$ and

$$\frac{W_1 = [\overline{Y'/Z}]N \qquad (\forall i)\ \Delta', \overline{P} \Vdash' [\overline{Y'/Z}]Q_i}{\Delta', \overline{P} \vdash' W_1 \leq \exists\overline{Z}\,\mathtt{where}\,\overline{Q}\,.\,N}$$

Using the inner I.H., we can easily verify that

$$(\forall i)\ [\overline{Y/X}]\Delta' \Vdash' [\overline{Y/X}][\overline{Y'/Z}]Q_i$$

Because the $\overline{Z}$ are sufficiently fresh, we may assume

$$[\overline{Y/X}](\exists\overline{Z}\,\mathtt{where}\,\overline{Q}\,.\,N) = \exists\overline{Z}\,\mathtt{where}\,([\overline{Y/X}]\overline{Q})\,.\,([\overline{Y/X}]N)$$
$$\overline{Z} \cap \overline{Y} = \emptyset$$

Moreover, for $s = \overline{[\overline{Y/X}]Y'/Z]}$, we have

$$[\overline{Y/X}][\overline{Y'/Z}]N = s[\overline{Y/X}]N$$
$$[\overline{Y/X}][\overline{Y'/Z}]\overline{Q} = s[\overline{Y/X}]\overline{Q}$$

Hence,

$$[\overline{Y/X}]W_1 = s[\overline{Y/X}]N$$
$$(\forall i)\ [\overline{Y/X}]\Delta' \Vdash' s[\overline{Y/X}]Q_i$$

The claim now follows with rule S$_3$-ABSTRACT'.

End case distinction on the last rule used in $\mathcal{D}$. □

Now we can prove that $\Delta \vdash T \leq U$ and $\Delta \vdash' T \leq U$ coincide.

Lemma 20 (Soundness and completeness). *$\Delta \vdash T \leq U$ if and only if $\Delta \vdash' T \leq U$.*

Proof. Both directions of the lemma are proved by a straightforward induction on the derivation given. For the "$\Rightarrow$" direction, we note two things:

- When the derivation of $\Delta \vdash T \leq U$ ends with rule S$_3$-TRANS, we apply the I.H. to the two subderivations and combine the two resulting derivations using Lemma 19.
- When the derivation of $\Delta \vdash T \leq U$ ends with rule S$_3$-ABSTRACT, we have $N = [\overline{T/X}]M$ as a premise. But the corresponding rule S$_3$-ABSTRACT' requires $N = [\overline{Y/X}]M$. We can easily show $\overline{T} = \overline{Y}$ for some $\overline{Y}$ because N has the form $C\texttt{<}\overline{Z}\texttt{>}$ (see the syntax in Fig. 4). □

Our next goal is to show that $[\![\Gamma]\!]^- \vdash' [\![\tau]\!]^- \leq [\![\tau']\!]^+$ implies $\Gamma \vdash \tau \leq \tau'$. Before proving this fact, we need to establish some more lemmas. In the following, we use the notation $\mathcal{D} :: \mathcal{J}$ to denote that $\mathcal{D}$ is a derivation for judgment $\mathcal{J}$ and define $\mathsf{height}(\mathcal{D})$ as the height of $\mathcal{D}$.

Lemma 21 (Strengthening). *Suppose $X \notin \mathsf{ftv}(\Delta, T, U, V)$. If $\mathcal{D} :: \Delta, X\,\texttt{super}\,T \vdash' U \leq V$ or $\mathcal{D} :: \Delta, X\,\texttt{extends}\,T \vdash' U \leq V$, then $\mathcal{D} :: \Delta \vdash' U \leq V$ with $\mathsf{height}(\mathcal{D}) = \mathsf{height}(\mathcal{D}')$.*

Proof. Straightforward induction on $\mathcal{D}$. □

Lemma 22.

(i) If $\mathcal{D} :: \Delta, X\,\texttt{super}\,T \vdash' U \leq X$ with $X \notin \mathsf{ftv}(\Delta, T, U)$, then $\mathcal{D}' :: \Delta \vdash' U \leq T$ with $\mathsf{height}(\mathcal{D}') \leq \mathsf{height}(\mathcal{D})$.

(ii) If $\mathcal{D} :: \Delta, X\,\texttt{extends}\,T \vdash' X \leq U$ with $X \notin \mathsf{ftv}(\Delta, T, U)$, then $\mathcal{D}' :: \Delta \vdash' T \leq U$ with $\mathsf{height}(\mathcal{D}') \leq \mathsf{height}(\mathcal{D})$.

Proof.

(i) Induction on $\mathcal{D}$.
Case distinction on the last rule of $\mathcal{D}$.
- *Case* rule S$_3$-REFL': Impossible.
- *Case* rule S$_3$-OBJECT': Impossible.
- *Case* rule S$_3$-EXTENDS': Follows by I.H. and rule S$_3$-EXTENDS'.
- *Case* rule S$_3$-SUPER': Then $\Delta, X\,\texttt{super}\,T \vdash' U \leq T$ from the premise and the claim follows with Lemma 21.
- *Case* rule S$_3$-OPEN': Then $U = \exists\overline{Y}\,\texttt{where}\,\overline{Q}\,.\,N$ and

$$\text{S}_3\text{-OPEN'}\ \frac{\text{S}_3\text{-SUPER'}\ \dfrac{\mathcal{D}_1 :: \Delta, X\,\texttt{super}\,T, \overline{Q} \vdash' N \leq T}{\Delta, X\,\texttt{super}\,T, \overline{Q} \vdash' N \leq X} \qquad \overline{Y} \cap \mathsf{ftv}(\Delta, X, T) = \emptyset}{\mathcal{D} :: \Delta, X\,\texttt{super}\,T \vdash' \exists\overline{Y}\,\texttt{where}\,\overline{Q}\,.\,N \leq X}$$

We have $X \notin \mathsf{ftv}(\overline{Q}, N)$ because $X \notin \mathsf{ftv}(U)$. With Lemma 21

$$\mathcal{D}_1' :: \Delta, \overline{Q} \vdash' N \leq T$$
$$\mathsf{height}(\mathcal{D}_1) = \mathsf{height}(\mathcal{D}_1')$$

The claim now follows with rule S$_3$-OPEN'.

– *Case* rule S$_3$-ABSTRACT': Impossible.

End case distinction on the last rule of $\mathcal{D}$.

(ii) *Case distinction* on the last rule of $\mathcal{D}$.

– *Case* rule S$_3$-REFL': Impossible.
– *Case* rule S$_3$-OBJECT': Trivial.
– *Case* rule S$_3$-EXTENDS': Then $\Delta, X\,\texttt{extends}\,T \vdash' T \leq U$ from the premise and the claim follows with Lemma 21.
– *Case* rule S$_3$-SUPER': Follows by I.H. and rule S$_3$-SUPER'.
– *Case* rule S$_3$-OPEN': Impossible.
– *Case* rule S$_3$-ABSTRACT': Impossible.

End case distinction on the last rule of $\mathcal{D}$. □

Lemma 23. *Let τ^- and σ^+ be $F^D_{\leq}$ types. Then $[\![\tau]\!]^- \neq [\![\sigma]\!]^+$.*

Proof. Obvious. □

Lemma 24. *If $[\![\Gamma]\!]^- \vdash' [\![\tau]\!]^- \leq [\![\tau']\!]^+$ then $\Gamma \vdash \tau \leq \tau'$.*

Proof. Let $[\![\Gamma]\!]^- = \Delta$, $[\![\tau]\!]^- = T$, and $[\![\tau']\!]^+ = U$. Proceed by induction on the given derivation.
Case distinction on the last rule of this derivation.

– *Case* rule S$_3$-REFL': Then $T = U$ so $[\![\tau]\!]^- = [\![\tau']\!]^+$ which is impossible by Lemma 23.
– *Case* rule S$_3$-OBJECT': Then $\tau' = \mathsf{Top}$ and the claim follows by D-TOP.
– *Case* rule S$_3$-EXTENDS': Then $T = X^\alpha$ and $\tau = \alpha$ and

$$\frac{X\,\texttt{extends}\,T' \in \Delta \qquad \Delta \vdash' T' \leq U}{\Delta \vdash' X^\alpha \leq U}$$

Because $\Delta = [\![\Gamma]\!]^-$, we have $T' = [\![\sigma]\!]^-$ and $\Gamma(\alpha) = \sigma^-$. Applying the I.H. yields

$$\Gamma \vdash \sigma \leq \tau'$$

so the claim follows by rule D-VAR.
– *Case* rule S$_3$-SUPER': Impossible because n-positive types are not variables.
– *Case* rule S$_3$-OPEN': Hence $T = \exists\overline{X}\,\texttt{where}\,\overline{P}\,.\,N$ and

$$\frac{\Delta, \overline{P} \vdash' N \leq T \qquad \overline{X} \cap \mathsf{ftv}(\Delta, U) = \emptyset}{\Delta \vdash' \exists\overline{X}\,\texttt{where}\,\overline{P}\,.\,N \leq U}$$

From $T = [\![\tau]\!]^-$ we have

$$\begin{aligned}
\tau &= \forall\alpha_0 \ldots \alpha_n\,.\,\neg\,\sigma \\
T &= \neg\,\overbrace{\exists X^{\alpha_0} \ldots X^{\alpha_n}\,Y\,\texttt{where}\,Y\,\texttt{extends}\,[\![\sigma]\!]^+\,.\,C^{n+2}\texttt{<}Y, X^{\alpha_0} \ldots X^{\alpha_n}\texttt{>}}^{=T'} \\
&= \exists X\,\texttt{where}\,X\,\texttt{super}\,T'\,.\,D^1\texttt{<}X\texttt{>}
\end{aligned}$$

From $U = [\![\tau']\!]^+$ we get that either $U = \texttt{Object}$ (then $\tau' = \mathsf{Top}$ and we are done) or that

$$\tau' = \forall \alpha_0 \leq \tau_0^- \ldots \alpha_n \leq \tau_n^- \,.\, \neg\, \sigma'$$

$$U = \neg \overbrace{\exists X^{\alpha_0} \ldots X^{\alpha_n}\, Y \,\texttt{where}\, X^{\alpha_0} \,\texttt{extends}\, [\![\tau_0]\!]^- \ldots \; X^{\alpha_n} \,\texttt{extends}\, [\![\tau_n]\!]^- \; Y \,\texttt{extends}\, [\![\sigma']\!]^- \,.\, C^{n+2}\texttt{<}Y, X^{\alpha_0} \ldots X^{\alpha_n}\texttt{>}}^{=U'}$$

$$= \exists X \,\texttt{where}\, X \,\texttt{super}\, U' \,.\, D^1\texttt{<}X\texttt{>}$$

From $\Delta \vdash' T \leq U$ we get by inverting the rules:

$$\textsc{s}_3\textsc{-open'}\ \frac{\textsc{s}_3\textsc{-abstract'}\ \dfrac{\textsc{e}_3\textsc{-super'}\ \dfrac{\mathcal{D} :: \Delta, X \,\texttt{super}\, T' \vdash' U' \leq X}{\Delta, X \,\texttt{super}\, T' \Vdash' X \,\texttt{super}\, U'}}{\Delta, X \,\texttt{super}\, T' \vdash' D^1\texttt{<}X\texttt{>} \leq \exists X \,\texttt{where}\, X \,\texttt{super}\, U' \,.\, D^1\texttt{<}X\texttt{>}} \quad X \notin \mathsf{ftv}(\Delta, U)}{\Delta \vdash' \exists X \,\texttt{where}\, X \,\texttt{super}\, T' \,.\, D^1\texttt{<}X\texttt{>} \leq \exists X \,\texttt{where}\, X \,\texttt{super}\, U' \,.\, D^1\texttt{<}X\texttt{>}}$$

We have $X \notin \mathsf{ftv}(\Delta, T', U')$ so with Lemma 22

$$\mathcal{D}' :: \Delta \vdash' U' \leq T'$$
$$\mathsf{height}(\mathcal{D}') \leq \mathsf{height}(\mathcal{D})$$

$\mathcal{D}'$ must end with rule $\textsc{s}_3$-$\textsc{open}$'. Define

$$\Delta' = \Delta, X^{\alpha_0} \,\texttt{extends}\, [\![\tau_0]\!]^-, \ldots, X^{\alpha_n} \,\texttt{extends}\, [\![\tau_n]\!]^-$$
$$\Delta'' = \Delta', Y \,\texttt{extends}\, [\![\sigma']\!]^-$$

Inverting the rules yields

$$\textsc{s}_3\textsc{-open'}\ \frac{\textsc{s}_3\textsc{-abstract'}\ \dfrac{\ldots \qquad \textsc{e}_3\textsc{-extends}\ \dfrac{\mathcal{D}'' :: \Delta'' \vdash' Y \leq [\![\sigma]\!]^+}{\Delta'' \Vdash' Y \,\texttt{extends}\, [\![\sigma]\!]^+} \qquad \ldots}{\Delta'' \vdash' C^{n+2}\texttt{<}Y, X^{\alpha_0} \ldots X^{\alpha_n}\texttt{>} \leq T'}}{\mathcal{D}' :: \Delta \vdash' U' \leq T'}$$

We have $Y \notin \mathsf{ftv}(\Delta', [\![\sigma']\!]^-, [\![\sigma]\!]^+)$. Hence with Lemma 22

$$\mathcal{D}''' :: \Delta' \vdash' [\![\sigma']\!]^- \leq [\![\sigma]\!]^+$$
$$\mathsf{height}(\mathcal{D}''') \leq \mathsf{height}(\mathcal{D}'')$$

Because $\mathcal{D}'''$ is smaller than the initial derivation, we can apply the I.H. and get

$$\Gamma, \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \tau_n \vdash \sigma' \leq \sigma$$

With rule D-ALL-NEG

$$\Gamma \vdash \forall \alpha_0 \ldots \alpha_n \,.\, \neg\, \sigma \leq \forall \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \tau_n \,.\, \neg\, \sigma'$$

as required.

– *Case* rule S3-ABSTRACT': Impossible because no class type N is in the image of the $[\![\cdot]\!]^-$ translation.

End case distinction on the last rule of this derivation. □

Our final goal is to prove that subtyping in $\mathcal{EX}_{uplo}$, restricted to the image of the translation defined in Fig. 6, coincides with subtyping in $F^D_{\leq}$. We first prove a standard weakening lemma.

Lemma 25 (Weakening). *If $\Delta \vdash T \leq U$ and $\Delta \subseteq \Delta'$ then $\Delta' \vdash T \leq U$.*

Proof. Straightforward induction on the derivation given. □

The next lemma show that the negation operator for types (defined in Fig. 6) allows us to swap the left- and right-hand sides of a subtyping judgment.

Lemma 26. *If $\Delta \vdash U \leq T$ then $\Delta \vdash \neg T \leq \neg U$.*

Proof. We have

$$\neg T = \exists X \,\mathtt{where}\, X \,\mathtt{super}\, T \,.\, D^1\texttt{<}X\texttt{>}$$
$$\neg U = \exists X \,\mathtt{where}\, X \,\mathtt{super}\, U \,.\, D^1\texttt{<}X\texttt{>}$$

Assume $\Delta \vdash U \leq T$. Then $\Delta, X \,\mathtt{super}\, T \vdash U \leq T$ with Lemma 25. Hence

$$\text{S3-OPEN}\ \frac{\text{S3-ABSTRACT}\ \dfrac{\text{E3-SUPER}\ \dfrac{\text{S3-SUPER}\ \dfrac{\Delta, X \,\mathtt{super}\, T \vdash U \leq T}{\Delta, X \,\mathtt{super}\, T \vdash U \leq X}}{\Delta, X \,\mathtt{super}\, T \Vdash X \,\mathtt{super}\, U}}{\Delta, X \,\mathtt{super}\, T \vdash D^1\texttt{<}X\texttt{>} \leq \exists X \,\mathtt{where}\, X \,\mathtt{super}\, U \,.\, D^1\texttt{<}X\texttt{>}} \quad X \notin \mathsf{ftv}(\Delta, \neg U)}{\Delta \vdash \exists X \,\mathtt{where}\, X \,\mathtt{super}\, T \,.\, D^1\texttt{<}X\texttt{>} \leq \exists X \,\mathtt{where}\, X \,\mathtt{super}\, U \,.\, D^1\texttt{<}X\texttt{>}}$$

□

The relation $\Delta \vdash \overline{P} \precsim \overline{Q}$, defined next, expresses that the constraints $\overline{P}$ are more specific than the constraints $\overline{Q}$.

Definition 27 ($\Delta \vdash \overline{P} \precsim \overline{P}$, $\Delta \vdash P \precsim P$).

$$\frac{(\forall i \in [n], \exists j \in [m])\ \Delta, \Delta_i \vdash P_j \precsim Q_i \text{ with } \Delta_i \subseteq \overline{P}}{\Delta \vdash \overline{P}^m \precsim \overline{Q}^n}$$

$$\frac{\Delta \vdash T \leq T'}{\Delta \vdash X \,\mathtt{extends}\, T \precsim X \,\mathtt{extends}\, T'} \qquad \frac{\Delta \vdash T' \leq T}{\Delta \vdash X \,\mathtt{super}\, T \precsim X \,\mathtt{super}\, T'}$$

We now connect $\precsim$ with subtyping on existentials.

Lemma 28. *If* $\Delta \vdash \overline{P} \precsim \overline{Q}$ *then* $\Delta \vdash \exists \overline{X}\,\mathtt{where}\,\overline{P}\,.\,N \leq \exists \overline{X}\,\mathtt{where}\,\overline{Q}\,.\,N$.

Proof. It is easy to see that $\Delta \vdash \overline{P} \precsim \overline{Q}$ implies $\Delta, \overline{P} \Vdash Q$ for all $Q \in \overline{Q}$. Then we have

$$\textsc{s}_3\textsc{-open}\ \frac{\textsc{s}_3\textsc{-abstract}\ \dfrac{(\forall i)\ \Delta, \overline{P} \Vdash Q_i}{\Delta, \overline{P} \vdash N \leq \exists \overline{X}\,\mathtt{where}\,\overline{Q}\,.\,N} \qquad \overline{X} \cap \mathsf{ftv}(\Delta, \exists \overline{X}\,\mathtt{where}\,\overline{Q}\,.\,N) = \emptyset}{\Delta \vdash \exists \overline{X}\,\mathtt{where}\,\overline{P}\,.\,N \leq \exists \overline{X}\,\mathtt{where}\,\overline{Q}\,.\,N}$$

□

To finish the proof of Theorem 9, we show that subtyping in $\mathcal{EX}_{uplo}$, restricted to the image of the translation defined in Fig. 6, coincides with subtyping in $F^D_{\leq}$.

Lemma 29. $\Gamma \vdash \tau \leq \tau'$ *if and only if* $[\![\Gamma \vdash \tau \leq \tau']\!]$.

Proof.

– Assume $\Gamma \vdash \tau \leq \tau'$. We proceed by induction on this derivation
Case distinction on the last rule used.
  - *Case* rule D-TOP: Then $[\![\tau']\!]^+ = \mathtt{Object}$ and the claim is obvious.
  - *Case* rule D-VAR: Then $\tau = \alpha$ and

$$\frac{\Gamma \vdash \Gamma(\alpha) \leq \tau' \qquad \tau' \neq \mathsf{Top}}{\Gamma \vdash \alpha \leq \tau'}$$

    Then

$$X^\alpha\ \mathtt{extends}\ [\![\Gamma(\alpha)]\!]^- \in [\![\Gamma]\!]^-$$

    and by the I.H.

$$[\![\Gamma]\!]^- \vdash [\![\Gamma(\alpha)]\!]^- \leq [\![\tau']\!]^+$$

    The claim now follows with rules $\textsc{s}_3$-EXTENDS and $\textsc{s}_3$-TRANS.
  - *Case* rule D-ALL-NEG: Then

$$\frac{\Gamma, \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \tau_n \vdash \sigma' \leq \sigma}{\Gamma \vdash \underbrace{\forall \alpha_0 \ldots \alpha_n\,.\,\neg\,\sigma}_{=\tau} \leq \underbrace{\forall \alpha_0 \leq \tau_0 \ldots \alpha_n \leq \tau_n\,.\,\neg\,\sigma'}_{=\tau'}}$$

    and

$$[\![\tau]\!]^- = \neg\ \overbrace{\begin{array}{r}\exists X^{\alpha_0} \ldots X^{\alpha_n}\ Y\ \mathtt{where}\ Y\ \mathtt{extends}\ [\![\sigma]\!]^+ \\ .\,C^{n+2}\texttt{<}Y, X^{\alpha_0} \ldots X^{\alpha_n}\texttt{>}\end{array}}^{=T}$$

$$[\![\tau']\!]^+ = \neg\ \overbrace{\begin{array}{r}\exists X^{\alpha_0} \ldots X^{\alpha_n}\ Y\ \mathtt{where}\ X^{\alpha_0}\ \mathtt{extends}\ [\![\tau_0]\!]^- \ldots \\ X^{\alpha_n}\ \mathtt{extends}\ [\![\tau_n]\!]^- \\ Y\ \mathtt{extends}\ [\![\sigma']\!]^- \\ .\,C^{n+2}\texttt{<}Y, X^{\alpha_0} \ldots X^{\alpha_n}\texttt{>}\end{array}}^{=U}$$

Define

$$\Delta = [\![\Gamma]\!]^-$$
$$\Delta' = \Delta, X^{\alpha_0}\ \texttt{extends}\ [\![\tau_0]\!]^- \dots X^{\alpha_n}\ \texttt{extends}\ [\![\tau_n]\!]^-$$

Note that $[\![\Gamma, \alpha_0 \le \tau_0 \dots \alpha_n \le \tau_n]\!]^- = \Delta'$.
We must show $\Delta \vdash \neg T \le \neg U$. By applying the I.H. we get

$$\Delta' \vdash [\![\sigma']\!]^- \le [\![\sigma]\!]^+$$

Thus

$$\Delta' \vdash Y\ \texttt{extends}\ [\![\sigma']\!]^- \precsim Y\ \texttt{extends}\ [\![\sigma]\!]^+$$

Hence

$$\Delta \vdash X^{\alpha_0}\ \texttt{extends}\ [\![\tau_0]\!]^- \dots X^{\alpha_n}\ \texttt{extends}\ [\![\tau_n]\!]^-, Y\ \texttt{extends}\ [\![\sigma']\!]^- \precsim Y\ \texttt{extends}\ [\![\sigma]\!]^+$$

By Lemma 28

$$\Delta \vdash U \le T$$

By Lemma 26

$$\Delta \vdash \neg T \le \neg U$$

End case distinction on the last rule used.

– Assume $[\![\Gamma \vdash \tau \le \tau']\!]$. Let

$$\Delta = [\![\Gamma]\!]^-$$
$$T = [\![\tau]\!]^-$$
$$U = [\![\tau']\!]^+$$

Hence, $\Delta \vdash T \le U$. By Lemma 20 we then have $\Delta \vdash' T \le U$. Thus, by Lemma 24, $\Gamma \vdash \tau \le \tau'$. □