Typed Operational Semantics for Higher Order Subtyping

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Abstract

Bounded operator abstraction is a language construct relevant to object oriented programming languages and to ML2000, the successor to Standard ML. In this paper, we introduce $\mathcal{F}^{\omega}_{\leq:}$, a variant of $F^{\omega}_{\leq:}$ with this feature and with Cardelli and Wegner's kernel Fun rule for quantifiers. We define a typed operational semantics with subtyping and prove that it is equivalent with $\mathcal{F}^{\omega}_{\leq:}$, using a Kripke model to prove soundness. The typed operational semantics provides a powerful tool to establish the metatheoretic properties of $\mathcal{F}^{\omega}_{\leq:}$, such as Church–Rosser, subject reduction, the admissibility of structural rules, and the equivalence with the algorithmic presentation of the system.

1 Introduction

During the last decade, object-oriented programming languages such as Smalltalk, C++, Modula 3, and Java have become popular because they encourage and facilitate software reuse and abstract design. In this time, the theoretical community has struggled to achieve a balance between safety and expressiveness of object-oriented programming languages, where safe languages use type systems to restrict the legal programs and thereby prevent errors, and expressive languages provide more constructs to allow the programmer to write programs more clearly or concisely.

A wide variety of language features has been proposed to model constructs from object-oriented programming languages in type systems, for example bounded quantification [15], recursive types [3], and matching [1, 6]. The feature we study in this paper is bounded abstraction on types, also called bounded operator abstraction. Cardelli and Harper are in favor of including this in ML2000 (private communication), the successor of Standard ML. The constructor is amply motivated by many examples due to Kim Bruce [5], including the following, which shows how bounded abstraction on types can be used to define the type of binary search trees with comparable elements:

$$\text{Comparable} = \Lambda X{:}\star.[\text{eq} : X \to X \to \text{Bool}, \text{lt} : X \to X \to \text{Bool}, \text{gt} : X \to X \to \text{Bool}]$$

$$\begin{array}{lll} \text{BinTree} = \Lambda X{:}\star.\Lambda Y{\leq}(\text{Comparable}\, X){:}\star.[& \text{find} & : Y \to \text{Bool}, \\ & \text{insert} & : Y \to \text{BinTree}, \\ & \text{isEmpty} & : \text{Bool}] \end{array}$$

The calculus we study in this paper, $\mathcal{F}^{\omega}_{\leq}$, is a minimal type theoretic presentation without all of the features needed to construct this example, such as object and recursive types. However, Abadi and Cardelli's study of the higher-order object calculus [2] has demonstrated that these object-oriented features do not present difficulties for the metatheory.

1.1 Syntactic Properties of Interest

We believe that type-checking for programming languages should be decidable. Type systems prevent basic programming errors by limiting the meaningful programs. While we want the type system to be powerful to allow more expressive programs, the type system should also have a low overhead for the programmer. In particular, the compiler should be able to recognize correct and incorrect programs reliably without help from the programmer.

For type systems with subtyping, an important aspect of decidable type-checking is the ability to eliminate instances of transitivity in subtyping. The transitivity rule leads to significant non-determinism, which in turn leads to infeasible subtyping algorithms. Thus existing algorithms for systems with decidable or semi-decidable subtyping [4, 10, 11, 21, 22] are syntax-directed in their search and only use transitivity in a specific, restricted way.

Another important property of a type system is subject reduction or type preservation, which states that evaluation of programs preserves their type. This is one of the central results of the paper. However, we also focus on the same property at the level of types, as well as showing strong normalization for types, which states that type reduction will always terminate. Both of these properties are needed to show the correctness of the algorithms for type-formation and subtyping.

1.2 Typed Operational Semantics and Metatheory

Adding bounded operator abstraction to $F^{\omega}_{<:}$ leads to complications in studying metatheoretic properties of the system. The new constructor means that subtyping is now needed to check well-formation of types, which because type-checking is needed in subtyping presents a circularity that together with β-equality is not trivial to study. In particular, we now need knowledge about subtyping to show results like subject reduction for types.

Most type systems with subtyping do not have this circularity: for example, $F^{\omega}_{<:}$ [7], $F^{\omega}_{\wedge}$ [12], and the systems in Abadi and Cardelli's book on objects [2] all separate the two judgements. Existing work on systems with such a circularity [4] avoids the interdependency by finding a particular order in which to prove results.

One contribution of this paper is to give a typed operational semantics for $\mathcal{F}^{\omega}_{\leq}$, extending work on dependent type theories [16, 17] to systems with subtyping. The typed operational semantics is an intermediate presentation of type formation and subtyping based on typed reduction, used as a tool for showing metatheoretic properties of the type system. The typed operational semantics avoids many problems due to the circularity by including extra structural information to allow proofs to go through.

Many metatheoretic properties are easier to establish with typed operational semantics than with traditional methods of reasoning about type systems. Because of the type information, the proof of completeness (corresponding to traditional proofs of correctness of an algorithm) here is simple. Furthermore, because the typed operational semantics essentially combines a reduction relation on types with an algorithm for subtyping, it does not have general structural rules such as substitution or weakening. This is reflected in the proof of

completeness, which is proved with respect to a system without the structural rules: hence, we show admissibility of these rules through the equivalence with the operational semantics.

Typed operational semantics also gives a clean conceptual division between soundness for the semantics and strong normalization. Our proof of strong normalization is a simple induction on derivations in the semantics, rather than an integral part of the model construction. Strong normalization for $\mathcal{F}^{\omega}_{\leq}$ is proved by composing the proofs of soundness for the semantics and strong normalization of the semantics. Subject reduction for types is also easier to prove in the typed operational semantics than in the original presentation. We refer the reader to the original papers [16, 17, 18] for a more complete description of this technique.

Including types in the operational description of the language makes many aspects of the metatheory of type theory easier. One crucial part of the development that becomes more difficult is soundness, corresponding to proofs of strong normalization. This proof now needs to keep type information, which in particular requires extra machinery to capture adding fresh variables to model binders. Hence, the proof of soundness is by a Kripke-style interpretation, using techniques developed by Coquand and Gallier [14].

In our treatment, we have only given a typed operational semantics for the language of types and kinds, and the subtyping relation. This is because the full term language is intended to have recursion operators and objects, so the terms will not be strongly normalizing. The analysis of the language of types is still important, because it gives us information about the decomposition of subtyping judgements that allows us to prove subject reduction for terms and to show important properties about the typechecking and subtyping algorithms.

2 Syntax

We now present the rules for kinding, subtyping, and typing in $\mathcal{F}^{\omega}_{\leq}$. They are organized as proof systems for several interdependent judgement forms:

$\Gamma \vdash \mathrm{ok}$	well-formed context
$\Gamma \vdash K$	well-formed kind
$\Gamma \vdash K = K'$	kind equality
$\Gamma \vdash A : K$	well-kinded type
$\Gamma \vdash A = B : K$	type equality
$\Gamma \vdash A \leq B : K$	subtype
$\Gamma \vdash M : A$	well-typed term.

We sometimes use the metavariable J to range over statements (right-hand sides of judgements) of any of these judgement forms.

2.1 Syntactic Categories

The *kinds* of $\mathcal{F}^{\omega}_{\leq}$ are the kind $\star$ of proper types and the kinds $\Pi X{\leq}A{:}K_1.K_2$ of functions on types (sometimes called type operators).

$\mathbb{K}$	::=	$\star$	types
		$\Pi X{\leq}\mathbb{A}{:}\mathbb{K}.\mathbb{K}$	type operators

The language of *types* of $\mathcal{F}^\omega_\leq$ is a straightforward higher-order extension of $F_\leq$, Cardelli and Wegner's second-order calculus of bounded quantification. Like $F_\leq$, it includes type variables X; function types $A{\to}B$; and polymorphic types $\forall X{\leq}A{:}K.B$, in which the bound type variable X ranges over all subtypes of the upper bound A. Moreover, like F^ω, we allow types to be abstracted on types, but we allow bounds on the abstraction $\Lambda X{\leq}A{:}K.B$. We can also apply types to argument types $A\,B$; in effect, these forms introduce a simply typed λ-calculus with subtyping at the level of types. We shall sometimes use the word "types" to mean types and type operators.

The capture-avoiding substitution of A for X in B is written $B[X{\leftarrow}A]$. We identify types that differ only in the names of bound variables. We shall write $A(B_1,\ldots,B_n)$ for $((A\,B_1)\ldots B_n)$. If A is of the form $X(B_1,\ldots,B_n)$ then A has head variable X. We write $\mathrm{HV}(--)$ for the partial function returning the head variable of a term. We also extend the top type $\mathrm{T}_\star$ to any kind K by defining inductively $\mathrm{T}_{\Pi X\leq A:K_1.K_2} = \Lambda X{\leq}A{:}K_1.\mathrm{T}_{K_2}$.

$\mathbb{A}$	::=	X	type variable
		$\mathbb{A}{\to}\mathbb{A}$	function type
		$\forall X{\leq}\mathbb{A}{:}\mathbb{K}.\mathbb{A}$	polymorphic type
		$\Lambda X{\leq}\mathbb{A}{:}\mathbb{K}.\mathbb{A}$	operator abstraction
		$\mathbb{A}\,\mathbb{A}$	operator application
		$\mathrm{T}_\star$	top type

The language of terms includes the variables (x), applications $(M\,N)$, and functional abstractions $(\lambda x{:}A.M)$ of the simply typed λ-calculus, as well as bounded type abstraction $(\lambda X{\leq}A{:}K.M)$ and application $(M\,A)$ of F^ω. As in $F_\leq$, each type variable is given an upper bound at the point where it is introduced. We use the same notation for capture-avoiding substitution as that for types, and again identify α-equivalent terms.

$\mathbb{M}$	::=	x	variable
		$\lambda x{:}\mathbb{A}.\mathbb{M}$	abstraction
		$\mathbb{M}\,\mathbb{M}$	application
		$\lambda X{\leq}\mathbb{A}{:}\mathbb{K}.\mathbb{M}$	type abstraction
		$\mathbb{M}\,\mathbb{A}$	type application

The operational semantics of $\mathcal{F}^\omega_\leq$ is given by the following reduction rules on terms and types.

DEFINITION 2.1 (*Untyped Reduction*)

1. $(\lambda x{:}A.e_1)e_2 \to_{\beta_1} e_1[x{\leftarrow}e_2]$
2. $(\lambda X{\leq}A{:}K_1.e)B \to_{\beta_1} e[X{\leftarrow}B]$
3. $(\Lambda X{\leq}A{:}K.B)C \to_{\beta_2} B[X{\leftarrow}C]$

Each relation ($\to_{\beta_1}$ and $\to_{\beta_2}$) is extended to a compatible relation with respect to term or type formation. The reduction $\to_\beta$ is defined by $\to_{\beta_1}\cup\to_{\beta_2}$. We write $\twoheadrightarrow_R$ for the transitive and reflexive closure of $\to_R$ and $=_R$ for the least equivalence relation containing $\to_R$. The β_2-normal form of a type A is written $\mathrm{nf}(A)$.

2.2 Contexts

A *context* Γ is a finite sequence of typing and subtyping assumptions for a set of term and type variables.

The empty context is written $\emptyset$. Term variable bindings have the form $x{:}A$; type variable bindings have the form $X{\leq}A{:}K$, where A is the upper bound of X and K is the kind of A.

Γ	::=	$\emptyset$	empty context
		$\Gamma,\, x{:}A$	term variable declaration
		$\Gamma,\, X{\leq}A{:}K$	type variable declaration

We call the set of term and type variables defined in a context Γ the *domain* of Γ, written $\mathrm{dom}(\Gamma)$. The functions $\mathrm{FV}(\text{—})$ gives the set of free term variables and free type variables of a term, type, context, or statement. Since we are careful to ensure that no variable is bound more than once, we sometimes abuse notation and consider contexts as finite functions: $\Gamma(X)$ yields the bound of X in Γ, where X is implicitly asserted to be in $\mathrm{dom}(\Gamma)$.

We now give the rules of inference for the system $\mathcal{F}^{\omega}_{\leq}$.

2.3 Structural Rules

This section presents general structural rules for $\mathcal{F}^{\omega}_{\leq}$. In fact, each of the rules is admissible, which we shall show when we prove the equivalence of this system with the typed operational semantics.

$$\frac{\Gamma \vdash A : \star \qquad \Gamma \vdash J \qquad x \notin \mathrm{dom}(\Gamma)}{\Gamma,\, x{:}A \vdash J} \tag{Weak}$$

$$\frac{\Gamma \vdash J \qquad \Gamma \vdash A : K \qquad X \notin \mathrm{dom}(\Gamma)}{\Gamma,\, X{\leq}A{:}K \vdash J} \tag{TWeak}$$

$$\frac{\Gamma_1,\, X{\leq}B{:}K,\, \Gamma_2 \vdash J \qquad \Gamma_1 \vdash A{\leq}B : K}{\Gamma_1,\, \Gamma_2[X{\leftarrow}A] \vdash J[X{\leftarrow}A]} \tag{Subst}$$

$$\frac{\Gamma_1,\, x{:}A,\, \Gamma_2 \vdash J \qquad \Gamma_1 \vdash A =_\beta B : \star}{\Gamma_1,\, X{:}B,\, \Gamma_2 \vdash J} \tag{Context-EQ}$$

$$\frac{\Gamma_1,\, X{\leq}A{:}K,\, \Gamma_2 \vdash J \qquad \Gamma_1 \vdash A =_\beta B : K \qquad \Gamma_1 \vdash K =_\beta K'}{\Gamma_1,\, X{\leq}B{:}K',\, \Gamma_2 \vdash J} \tag{Context-T-EQ}$$

$$\frac{\Gamma \vdash B : K}{\Gamma \vdash K} \tag{Kind-Agreement}$$

2.4 Context Formation

The context formation rules are:

$$\emptyset \vdash \mathrm{ok} \tag{C-Empty}$$

$$\frac{\Gamma \vdash A : \star \qquad x \notin \mathrm{dom}(\Gamma)}{\Gamma,\, x{:}A \vdash \mathrm{ok}} \tag{C-Var}$$

$$\frac{\Gamma \vdash A : K \qquad X \notin \mathrm{dom}(\Gamma)}{\Gamma,\, X{\leq}A{:}K \vdash \mathrm{ok}} \tag{C-TVar}$$

2.5 Kind Formation

The well-formed kinds are those derived with the following rules.

$$\frac{\Gamma \vdash \text{ok}}{\Gamma \vdash \star} \qquad \text{(K-}\star\text{)}$$

$$\frac{\Gamma,\, X{\leq}A{:}K_1 \vdash K_2}{\Gamma \vdash \Pi X{\leq}A{:}K_1.K_2} \qquad \text{(K-}\Pi\text{)}$$

2.6 Kind Equality

The interconvertibility of kinds is the propagation of the interconvertibility of types within kinds.

$$\frac{\Gamma \vdash K}{\Gamma \vdash K =_\beta K} \qquad \text{(K-Eq-Refl)}$$

$$\frac{\Gamma \vdash K =_\beta K'}{\Gamma \vdash K' =_\beta K} \qquad \text{(T-Eq-Sym)}$$

$$\frac{\Gamma \vdash K =_\beta K' \qquad \Gamma \vdash K' =_\beta K''}{\Gamma \vdash K =_\beta K''} \qquad \text{(T-Eq-Trans)}$$

$$\frac{\Gamma \vdash \text{ok}}{\Gamma \vdash \star =_\beta \star} \qquad \text{(K-Eq-}\star\text{)}$$

$$\frac{\Gamma \vdash K_1 =_\beta K_1' \qquad \Gamma \vdash A =_\beta A' : K_1 \qquad \Gamma,\, X{\leq}A{:}K_1 \vdash K_2 =_\beta K_2'}{\Gamma \vdash \Pi X{\leq}A{:}K_1.K_2 =_\beta \Pi X{\leq}A'{:}K_1'.K_2'} \qquad \text{(K-Eq-}\Pi\text{)}$$

2.7 Type Formation

For each type constructor, we give a rule specifying how it can be used to build well-formed type expressions. The new rules for type formation are the ones that deal with bounded type abstraction (T-TAbs), type application (T-TApp), and kind conversion (T-Conv).

$$\frac{\Gamma \vdash \text{ok}}{\Gamma \vdash \mathrm{T}_\star : \star} \qquad \text{(T-Top)}$$

$$\frac{\Gamma_1,\, X{\leq}A{:}K,\, \Gamma_2 \vdash \text{ok}}{\Gamma_1,\, X{\leq}A{:}K,\, \Gamma_2 \vdash X : K} \qquad \text{(T-TVar)}$$

$$\frac{\Gamma \vdash A_1 : \star \qquad \Gamma \vdash A_2 : \star}{\Gamma \vdash A_1{\to}A_2 : \star} \qquad \text{(T-Arrow)}$$

$$\frac{\Gamma,\, X{\leq}A_1{:}K \vdash A_2 : \star}{\Gamma \vdash \forall X{\leq}A_1{:}K.A_2 : \star} \qquad \text{(T-All)}$$

$$\frac{\Gamma,\, X{\leq}A_1{:}K_1 \vdash A_2 : K_2}{\Gamma \vdash \Lambda X{\leq}A_1{:}K_1.A_2 : \Pi X{\leq}A_1{:}K_1.K_2} \qquad \text{(T-TAbs)}$$

$$\frac{\Gamma \vdash A : \Pi X{\leq}B{:}K_1.K_2 \qquad \Gamma \vdash C{\leq}B : K_1}{\Gamma \vdash A\,C : K_2[X{\leftarrow}C]} \qquad \text{(T-TApp)}$$

$$\frac{\Gamma \vdash A : K \qquad \Gamma \vdash K =_\beta K'}{\Gamma \vdash A : K'} \qquad \text{(T-Conv)}$$

2.8 Type Equality

The judgemental type equality is generated by the typed beta-equality rule (T-Eq-Beta). It is a congruence with respect to type formation and incorporates kind equivalence so that equal kinds contain the same equality relation on types.

$$\frac{\Gamma,\, X{\leq}A_1{:}K_1 \vdash A_2 : K_2 \qquad \Gamma \vdash C \leq A_1 : K_1}{\Gamma \vdash (\Lambda X{\leq}A_1{:}K_1.A_2)\, C =_\beta A_2[X{\leftarrow}C] : K_2[X{\leftarrow}C]} \quad \text{(T-Eq-Beta)}$$

$$\frac{\Gamma \vdash A : K}{\Gamma \vdash A =_\beta A : K} \quad \text{(T-Eq-Refl)}$$

$$\frac{\Gamma \vdash A =_\beta B : K}{\Gamma \vdash B =_\beta A : K} \quad \text{(T-Eq-Sym)}$$

$$\frac{\Gamma \vdash A =_\beta B : K \qquad \Gamma \vdash B =_\beta C : K}{\Gamma \vdash A =_\beta C : K} \quad \text{(T-Eq-Trans)}$$

$$\frac{\Gamma \vdash A_1 =_\beta B_1 : \star \qquad \Gamma \vdash A_2 =_\beta B_2 : \star}{\Gamma \vdash A_1{\to}A_2 =_\beta B_1{\to}B_2 : \star} \quad \text{(T-Eq-Arrow)}$$

$$\frac{\Gamma \vdash A_1 =_\beta B_1 : K \qquad \Gamma,\, X{\leq}A_1{:}K \vdash A_2 =_\beta B_2 : \star \qquad \Gamma \vdash K =_\beta K'}{\Gamma \vdash \forall X{\leq}A_1{:}K.A_2 =_\beta \forall X{\leq}B_1{:}K'.B_2 : \star} \quad \text{(T-Eq-All)}$$

$$\frac{\Gamma \vdash A_1 =_\beta B_1 : K_1 \qquad \Gamma,\, X{\leq}A_1{:}K_1 \vdash A_2 =_\beta B_2 : K_2 \qquad \Gamma \vdash K_1 =_\beta K_1'}{\Gamma \vdash \Lambda X{\leq}A_1{:}K_1.A_2 =_\beta \Lambda X{\leq}B_1{:}K_1'.B_2 : \Pi X{\leq}A_1{:}K_1.K_2} \quad \text{(T-Eq-TAbs)}$$

$$\frac{\Gamma \vdash A =_\beta B : \Pi X{\leq}E{:}K_1.K_2 \qquad \Gamma \vdash C =_\beta D : K_1 \qquad \Gamma \vdash C \leq E : K_1}{\Gamma \vdash A\, C =_\beta B\, D : K_2[X{\leftarrow}C]} \quad \text{(T-Eq-TApp)}$$

$$\frac{\Gamma \vdash A =_\beta B : K \qquad \Gamma \vdash K =_\beta K'}{\Gamma \vdash A =_\beta B : K'} \quad \text{(T-Eq-Conv)}$$

2.9 Subtyping

The subtyping rules are those of $F^\omega_{<:}$[7], except for those dealing with bounded type abstraction and type application shown below and the rule for subtyping the quantifier. We chose the Cardelli and Wegner's kernel Fun rule for quantifiers with equal bounds [8]. The contravariant rule for quantifiers renders the system undecidable, and transitivity elimination in the presence of such a rule in the higher-order case remains an open problem.

$$\frac{\Gamma \vdash A : K}{\Gamma \vdash A \leq \mathrm{T}_K : K} \quad \text{(S-Top)}$$

$$\frac{\Gamma \vdash A =_\beta B : K}{\Gamma \vdash A \leq B : K} \quad \text{(S-Conv)}$$

$$\frac{\Gamma \vdash A \leq B : K \qquad \Gamma \vdash B \leq C : K}{\Gamma \vdash A \leq C : K} \quad \text{(S-Trans)}$$

$$\frac{\Gamma_1,\, X{\leq}A{:}K,\, \Gamma_2 \vdash \mathrm{ok}}{\Gamma_1,\, X{\leq}A{:}K,\, \Gamma_2 \vdash X \leq A : K} \quad \text{(S-TVar)}$$

$$\frac{\Gamma \vdash B_1 \leq A_1 : \star \qquad \Gamma \vdash A_2 \leq B_2 : \star}{\Gamma \vdash A_1{\to}A_2 \leq B_1{\to}B_2 : \star} \quad \text{(S-Arrow)}$$

$$\frac{\Gamma,\, X{\leq}C{:}K \vdash A \leq B : \star}{\Gamma \vdash \forall X{\leq}C{:}K.A \leq \forall X{\leq}C{:}K.B : \star} \quad \text{(S-All)}$$

$$\frac{\Gamma,\, X{\leq}C{:}K_1 \vdash A \leq B : K_2}{\Gamma \vdash \Lambda X{\leq}C{:}K_1.A \leq \Lambda X{\leq}C{:}K_1.B : \Pi X{\leq}C{:}K_1.K_2} \quad \text{(S-TAbs)}$$

$$\frac{\Gamma \vdash A \leq B : \Pi X{\leq}D{:}K_1.K_2 \qquad \Gamma \vdash C \leq D : K_1}{\Gamma \vdash A\,C \leq B\,C : K_2[X{\leftarrow}C]} \quad \text{(S-TApp)}$$

$$\frac{\Gamma \vdash A \leq B : K \qquad \Gamma \vdash K =_\beta K'}{\Gamma \vdash A \leq B : K'} \quad \text{(S-K-Conv)}$$

2.10 Term Formation

The term formation rules are those of the second-order calculus of bounded quantification with the difference that we include kind annotations in terms, types, contexts, and subtyping judgements.

$$\frac{\Gamma_1,\, x{:}A,\, \Gamma_2 \vdash \text{ok}}{\Gamma_1,\, x{:}A,\, \Gamma_2 \vdash x : A} \quad \text{(T-Var)}$$

$$\frac{\Gamma,\, x{:}A \vdash M : B}{\Gamma \vdash \lambda x{:}A.M : A{\to}B} \quad \text{(T-Abs)}$$

$$\frac{\Gamma \vdash M : A{\to}B \qquad \Gamma \vdash N : A}{\Gamma \vdash M\,N : B} \quad \text{(T-App)}$$

$$\frac{\Gamma,\, X{\leq}A{:}K \vdash M : B}{\Gamma \vdash \lambda X{\leq}A{:}K.M : \forall X{\leq}A{:}K.B} \quad \text{(T-TAbs)}$$

$$\frac{\Gamma \vdash M : \forall X{\leq}A{:}K.B \qquad \Gamma \vdash C \leq A : K}{\Gamma \vdash M\,C : B[X{\leftarrow}C]} \quad \text{(T-TApp)}$$

$$\frac{\Gamma \vdash M : A \qquad \Gamma \vdash A \leq B : \star}{\Gamma \vdash M : B} \quad \text{(T-Sub)}$$

3 The Typed Operational Semantics

The typed operational semantics for $\mathcal{F}^{\omega}_{\leq}$ is organized in five judgement forms.

$\Gamma \vdash_S \text{ok}$	well-formed context
$\Gamma \vdash_S K \twoheadrightarrow_{\text{n}} K'$	kind normalization
$\Gamma \vdash_S A \twoheadrightarrow_{\text{w}} B \;{}_{\text{w}}\!\twoheadrightarrow_{\text{n}} C : K$	type reduction
$\Gamma \vdash_S A \leq_W B : K$	weak-head subtyping
$\Gamma \vdash_S A \leq B : K$	subtyping

The informal meaning of these judgements is as follows. In $\Gamma \vdash_S K \twoheadrightarrow_{\text{n}} K'$, K' is the normal form of K. In $\Gamma \vdash_S A \twoheadrightarrow_{\text{w}} B \;{}_{\text{w}}\!\twoheadrightarrow_{\text{n}} C : K$, B is the weak head normal form of A and C its normal form. In $\Gamma \vdash_S A \leq_W B : K$, A and B are in weak head normal form, and in $\Gamma \vdash_S A \leq B : K$, A and B are arbitrary types or type operators.

Definition 3.1 (*Weak-Head Normal*)

$\text{T}_\star$, $A_1{\to}A_2$, $\forall X{\leq}A{:}K.B$, and $\Lambda X{\leq}A{:}K.B$ are weak head normal.

$X(A_1, \ldots, A_n)$ is weak head normal if $A_1, \ldots, A_n$ are in normal form.

In order to prove the admissibility of transitivity in the semantics, we need to consider a stronger definition of weak head normal form. We consider expressions of the form $X(A_1, \ldots, A_n)$ weak head normal only if each A_i is fully normalized. It may be possible to strengthen the model in Section 5 and use the standard definition of this notion instead.

We use the following notations:

- $\Gamma \vdash_S A : K$ is notation for $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$, for some B, C.
- $\Gamma \vdash_S K$ is notation for $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$, for some K'.
- $\Gamma \vdash_S A \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} B : K$ is notation for $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} A \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} B : K$.
- $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B : K$ is notation for $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$, for some C.
- $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{n}} B : K$ means $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} C \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} B : K$, for some C.
- $\Gamma \vdash_S A, B \twoheadrightarrow_{\mathrm{n}} C : K$ means $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{n}} C : K$ and $\Gamma \vdash_S B \twoheadrightarrow_{\mathrm{n}} C : K$.
- $\Gamma \vdash_S K, K' \twoheadrightarrow_{\mathrm{n}} K''$ means $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K''$ and $\Gamma \vdash_S K' \twoheadrightarrow_{\mathrm{n}} K''$.

The rules are presented as simultaneously defined inductive relations.

3.1 Context Formation

$$\emptyset \vdash_S \mathrm{ok} \tag{SC-Empty}$$

$$\frac{\Gamma \vdash_S A : \star \qquad x \notin \mathrm{dom}(\Gamma)}{\Gamma,\, x{:}A \vdash_S \mathrm{ok}} \tag{SC-Var}$$

$$\frac{\Gamma \vdash_S A : K' \qquad \Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K' \qquad X \notin \mathrm{dom}(\Gamma)}{\Gamma,\, X{\leq}A{:}K \vdash_S \mathrm{ok}} \tag{SC-TVar}$$

3.2 Kind Normalization

$$\frac{\Gamma \vdash_S \mathrm{ok}}{\Gamma \vdash_S \star \twoheadrightarrow_{\mathrm{n}} \star} \tag{SK-$\star$}$$

$$\frac{\Gamma \vdash_S K_1 \twoheadrightarrow_{\mathrm{n}} K_1' \qquad \Gamma \vdash_S A \twoheadrightarrow_{\mathrm{n}} B : K_1' \qquad \Gamma,\, X{\leq}A : K_1 \vdash_S K_2 \twoheadrightarrow_{\mathrm{n}} K_2'}{\Gamma \vdash_S \Pi X{\leq}A{:}K_1.K_2 \twoheadrightarrow_{\mathrm{n}} \Pi X{\leq}B{:}K_1'.K_2'} \tag{SK-Π}$$

Context formation and kind normalization rules follow from modifications to the context formation and kind equality rules of the system in Section 2.2. For example, in the type variable rule (ST-TVar) the kind of A and the kind in the declaration of X are β-equal but not necessarily identical.

3.3 Type Reduction

$$\frac{\Gamma \vdash_S \mathrm{ok}}{\Gamma \vdash_S \mathrm{T}_\star \twoheadrightarrow_{\mathrm{w}} \mathrm{T}_\star \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} \mathrm{T}_\star : \star} \tag{ST-Top}$$

$$\frac{\Gamma \vdash_S A : K' \qquad \Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K' \qquad (X{\leq}A : K) \in \Gamma}{\Gamma \vdash_S X \twoheadrightarrow_{\mathrm{w}} X \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} X : K'} \tag{ST-TVar}$$

$$\frac{\begin{array}{ll}\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} D : \Pi X{\leq}C{:}K_1.K_2 & \Gamma \vdash_S E \leq_W C : K_1 \\ \Gamma \vdash_S B \twoheadrightarrow_{\mathrm{w}} E \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} F : K_1 & \Gamma \vdash_S K_2[X{\leftarrow}B] \twoheadrightarrow_{\mathrm{n}} K \quad D \neq \Lambda Y{\leq}G{:}K_3.H\end{array}}{\Gamma \vdash_S A\,B \twoheadrightarrow_{\mathrm{w}} D\,F \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} D\,F : K} \tag{ST-TApp}$$

$$\frac{\Gamma \vdash_S A_1 \twoheadrightarrow_{\mathrm{n}} B_1 : \star \qquad \Gamma \vdash_S A_2 \twoheadrightarrow_{\mathrm{n}} B_2 : \star}{\Gamma \vdash_S (A_1 \to A_2) \twoheadrightarrow_{\mathrm{w}} (A_1 \to A_2) \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} (B_1 \to B_2) : \star} \quad \text{(ST-Arrow)}$$

$$\frac{\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{n}} C : K' \qquad \Gamma, X \leq A{:}K \vdash_S B \twoheadrightarrow_{\mathrm{n}} D : \star \qquad \Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'}{\Gamma \vdash_S \forall X \leq A{:}K.B \twoheadrightarrow_{\mathrm{w}} \forall X \leq A{:}K.B \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} \forall X \leq C{:}K'.D : \star} \quad \text{(ST-All)}$$

$$\frac{\Gamma \vdash_S K_1 \twoheadrightarrow_{\mathrm{n}} K_1' \qquad \Gamma \vdash_S A \twoheadrightarrow_{\mathrm{n}} C : K_1' \qquad \Gamma, X \leq A{:}K_1 \vdash_S B \twoheadrightarrow_{\mathrm{n}} D : K_2}{\Gamma \vdash_S \Lambda X \leq A{:}K_1.B \twoheadrightarrow_{\mathrm{w}} \Lambda X \leq A{:}K_1.B \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} \Lambda X \leq C{:}K_1'.D : \Pi X \leq C{:}K_1'.K_2} \quad \text{(ST-TAbs)}$$

$$\frac{\begin{array}{ll} \Gamma \vdash_S B \twoheadrightarrow_{\mathrm{w}} \Lambda X \leq A{:}K_1.D : \Pi X \leq A'{:}K_1'.K_2 & \Gamma \vdash_S K_2[X \leftarrow C] \twoheadrightarrow_{\mathrm{n}} K \\ \Gamma \vdash_S D[X \leftarrow C] \twoheadrightarrow_{\mathrm{w}} E \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} F : K & \Gamma \vdash_S C \leq A : {K_1}' \end{array}}{\Gamma \vdash_S B\,C \twoheadrightarrow_{\mathrm{w}} E \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} F : K} \quad \text{(ST-Beta)}$$

The rules for type reduction combine kinding information and computational behavior in the form of weak head and β-normal forms. For example, the rule for arrow types says how to obtain the weak head and β-normal form of $(A_1 \to A_2)$ in $\star$ knowing those for A_1 and A_2 in $\star$ as well.

The beta rule, besides uncovering the outermost redex of the application $B\,C$, and contracting it, finds the weak head normal form E and the normal form F. The premise $\Gamma \vdash_S K_2[X \leftarrow C] \twoheadrightarrow_{\mathrm{w}} K$ ensures that E and F have β-equal kinds, and the subtyping premise $\Gamma \vdash_S C \leq A : {K_1}'$ enforces the well-formation of $B\,C$.

The subtyping relation is defined using two judgements: one deals with types in weak head normal form ($\Gamma \vdash_S A \leq_W B : K$) and the other with arbitrary types ($\Gamma \vdash_S A \leq B : K$).

3.4 Weak Head Subtyping

$$\frac{\Gamma \vdash_S A \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} B : \star \qquad \mathrm{HV}(A) \text{ undefined}}{\Gamma \vdash_S A \leq_W \mathrm{T}_\star : \star} \quad \text{(SWS-Top)}$$

$$\frac{\begin{array}{ll} \Gamma \vdash_S X(A_1, \ldots, A_m) \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} C : K & \\ \Gamma \vdash_S \Gamma(X) \twoheadrightarrow_{\mathrm{n}} B : K' & \Gamma \vdash_S E \leq_W A : K \\ \Gamma \vdash_S B(A_1, \ldots, A_m) \twoheadrightarrow_{\mathrm{w}} E : K & A \neq X(A_1, \ldots, A_m) \end{array}}{\Gamma \vdash_S X(A_1, \ldots, A_m) \leq_W A : K} \quad \text{(SWS-TApp)}$$

$$\frac{\Gamma \vdash_S X(A_1, \ldots, A_m) \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} B : K}{\Gamma \vdash_S X(A_1, \ldots, A_m) \leq_W X(A_1, \ldots, A_m) : K} \quad \text{(SWS-Refl)}$$

$$\frac{\Gamma \vdash_S B_1 \leq A_1 : \star \qquad \Gamma \vdash_S A_2 \leq B_2 : \star}{\Gamma \vdash_S A_1 \to A_2 \leq_W B_1 \to B_2 : \star} \quad \text{(SWS-Arrow)}$$

$$\frac{\begin{array}{ll} \Gamma, X \leq A_1{:}K \vdash_S A_2 \leq B_2 : \star & \\ \Gamma \vdash_S A_1, B_1 \twoheadrightarrow_{\mathrm{n}} C : K'' & \Gamma \vdash_S K, K' \twoheadrightarrow_{\mathrm{n}} K'' \end{array}}{\Gamma \vdash_S \forall X \leq A_1{:}K.A_2 \leq_W \forall X \leq B_1{:}K'.B_2 : \star} \quad \text{(SWS-All)}$$

$$\frac{\begin{array}{ll} & \Gamma \vdash_S K_1, K_1' \twoheadrightarrow_{\mathrm{n}} K_1'' \\ \Gamma, X \leq A_1{:}K_1 \vdash_S A_2 \leq B_2 : K_2 & \Gamma \vdash_S A_1, B_1 \twoheadrightarrow_{\mathrm{n}} C : K_1'' \end{array}}{\Gamma \vdash_S \Lambda X \leq A_1{:}K_1.A_2 \leq_W \Lambda X \leq B_1{:}K_1'.B_2 : \Pi X \leq C{:}K_1''.K_2} \quad \text{(SWS-TAbs)}$$

The weak head subtyping rules are motivated by the algorithmic rules in [11]. The rules SWS-Arrow, SWS-All, and SWS-TAbs are structural. The rule for the maximal type $\mathrm{T}_\star$ has a side condition to ensure that the algorithm is deterministic, and applications are only handled by SWS-TApp or SWS-Refl.

A particular instance of SWS-TApp is the rule for type variables. To check if $\Gamma \vdash_S X \leq_W A : K$, we have to check that the bound of X in Γ is a subtype of A, $\Gamma \vdash_S \Gamma(X) \leq A : K$, and since we know that A is in weak head normal form we save a recursive call of SS-Inc and normalize $\Gamma(X)$ in a premise. The side condition $A \not\equiv X$ is to ensure determinism; if $A \equiv X$, it follows by reflexivity.

3.5 Subtyping

$$\frac{\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} C : K \qquad \Gamma \vdash_S B \twoheadrightarrow_{\mathrm{w}} D : K \qquad \Gamma \vdash_S C \leq_W D : K}{\Gamma \vdash_S A \leq B : K} \qquad \text{(SS-Inc)}$$

There is no rule for transitivity of subtyping in the semantic rules, but transitivity is a property of the "operational" subtyping (Lemma 4.21). Moreover, the rule SWS-TApp includes a step of transitivity along the bound of a variable in the context. We interleave weak head normalization steps in the subtyping algorithm via SS-Inc. An alternative formulation would weak head normalize the arguments of the hypothesis.

4 Metatheory for $\mathcal{F}^{\omega}_{\leq}$

In this section we prove fundamental properties about $\mathcal{F}^{\omega}_{\leq}$. We begin with results about the typed operational semantics and then show some basic results needed for the soundness proof for the system $\mathcal{F}^{\omega}_{\leq}$.

4.1 Metatheory for the Typed Operational Semantics

Here, the typed operational semantics is playing the same role as the algorithm in the usual development of the metatheory, but it also allows us to show results such as subject reduction and strong normalization for types.

Definition 4.1 (*Closed*)

1. A term M is closed with respect to a context Γ if $\mathrm{FV}(M) \cup \mathrm{FTV}(M) \subseteq \mathrm{dom}(\Gamma)$.
2. A type A is closed with respect to a context Γ if $\mathrm{FTV}(A) \subseteq \mathrm{dom}(\Gamma)$.

Judgements are closed if each of the terms to the right of the turnstile is closed with respect to the context.

Lemma 4.2 (*Closure*) If $\Gamma \vdash_S J$ then $\Gamma \vdash_S J$ is closed.

Lemma 4.3 (*Weak Head and Normal Forms*)

1. If $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$ then K' is in normal form.
2. If $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$ then B is in weak head normal form and C and K are in normal form.

Proof: By simultaneous induction on derivations. □

Lemma 4.4 (*Context Formation*) If $\Gamma \vdash_S J$ then there is a (not necessarily strict) subderivation of $\Gamma \vdash_S \mathrm{ok}$.

PROOF: By induction on derivations. □

LEMMA 4.5 (*Determinacy*) If $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$ and $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} D \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} E : K'$ then $B \equiv D$, $C \equiv E$ and $K \equiv K'$.

PROOF: By induction on derivations. □

As we mentioned in the introduction, we want to prove completeness with respect to a system without the structural rules in Section 2.3. We shall write $\Gamma \vdash^{-} J$ for judgements in the restricted system without these rules.

PROPOSITION 4.6 (*Completeness*)

1. $\Gamma \vdash_S$ ok implies $\Gamma \vdash^{-}$ ok.
2. $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$ implies $\Gamma \vdash^{-} K$ and $\Gamma \vdash^{-} K =_\beta K'$.
3. $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$ implies $\Gamma \vdash^{-} A : K$, $\Gamma \vdash^{-} A =_\beta B : K$, $\Gamma \vdash^{-} A =_\beta C : K$, and $\Gamma \vdash^{-} K =_\beta K$.
4. $\Gamma \vdash_S A \leq_W B : K$ implies $\Gamma \vdash^{-} A \leq B : K$.
5. $\Gamma \vdash_S A \leq B : K$ implies $\Gamma \vdash^{-} A, B : K$, $\Gamma \vdash^{-} A \leq B : K$ and $\Gamma \vdash^{-} K =_\beta K$.

PROOF: By simultaneous induction on derivations. We proceed by case analysis on the last rule of the derivation, presenting here a few representative cases. The hypotheses in each case are left implicit and follow exactly the notation of the rules in Section 3.

1. SC-EMPTY Immediate by C-EMPTY.

   SC-VAR By the induction hypothesis 3, $\Gamma \vdash A : \star$ and, by C-VAR, the result follows.

   SC-TVAR By the induction hypothesis 3,$\Gamma \vdash A : K'$, by the induction hypothesis 2, $\Gamma \vdash^{-} K =_\beta K'$. By the symmetry of kind equality and T-CONV, $\Gamma \vdash^{-} A : K$, and, by C-TVAR, the result follows.

2. SK-$\star$ By the induction hypothesis 1 $\Gamma \vdash^{-}$ ok. By K-$\star$, $\Gamma \vdash^{-} \star$, and, by K-EQ-$\star$, $\Gamma \vdash^{-} \star =_\beta \star$.

   SK-Π By the induction hypothesis 2, Γ, $X{\leq}A{:}K_1 \vdash^{-} K_2$, by the induction hypothesis 3, $\Gamma \vdash^{-} A : K_1'$. By the induction hypothesis 2, $\Gamma \vdash^{-} K_1 =_\beta K_1'$. By the symmetry of kind equality and T-CONV, $\Gamma \vdash^{-} A : K_1$. Then, by K-$\Pi$, $\Gamma \vdash^{-} \Pi X{\leq}A{:}K_1.K_2$. By the induction hypothesis 3, $\Gamma \vdash^{-} A =_\beta B : K_1$, and by the induction hypothesis 2 Γ, $X{\leq}A{:}K_1 \vdash^{-} K_2 =_\beta K_2'$. By K-EQ-$\Pi$, $\Gamma \vdash^{-} \Pi X{\leq}A{:}K_1.K_2 =_\beta \Pi X{\leq}B{:}K_1'.K_2'$.

3. ST-TAPP By the induction hypothesis 3, $\Gamma \vdash^{-} A : \Pi X{\leq}C{:}K_1.K_2$ and $\Gamma \vdash^{-} B =_\beta E : K_1$. By the induction hypothesis 5, $\Gamma \vdash^{-} E \leq C : K_1$. By S-CONV, $\Gamma \vdash^{-} B \leq E : K_1$, and, by S-TRANS, $\Gamma \vdash^{-} B \leq C : K_1$. By T-TAPP, $\Gamma \vdash^{-} A\,B : K_2[X{\leftarrow}B]$. By the induction hypothesis 2, $\Gamma \vdash^{-} K_2[X{\leftarrow}B] =_\beta K$, and, by T-CONV, $\Gamma \vdash^{-} A\,B : K$. We now have to prove that $\Gamma \vdash^{-} A\,B =_\beta D\,F : K$. By the induction hypothesis 3, $\Gamma \vdash^{-} A =_\beta D : \Pi X{\leq}C{:}K_1.K_2$. By T-EQ-TAPP, $\Gamma \vdash^{-} A\,B =_\beta D\,F : K_2[X{\leftarrow}B]$, and by T-EQ-CONV, $\Gamma \vdash^{-} A\,B =_\beta D\,F : K$.

4. SWS-All By inductive hypothesis 5, $\Gamma, X{\leq}A_1{:}K \vdash^{-} A_2 \leq B_2 : \star$ and $\Gamma, X{\leq}A_1{:}K \vdash^{-} B_2 : \star$. Then, by S-All, $\Gamma \vdash^{-} \forall X{\leq}A_1{:}K.A_2 \leq \forall X{\leq}A_1{:}K.B_2 : \star$. We now want to prove using T-EQ-All that $\Gamma \vdash^{-} \forall X{\leq}A_1{:}K.B_2 \leq \forall X{\leq}B_1{:}K'.B_2 : \star$. The result then follows by S-Conv and S-Trans. For that we need:
   (a) $\Gamma, X{\leq}A_1{:}K \vdash^{-} B_2 =_\beta B_2 : \star$, which follows from T-EQ-Refl.
   (b) $\Gamma \vdash^{-} K =_\beta K'$, which follows from the induction hypothesis 2, K-EQ-Sym and K-EQ-Trans.
   (c) $\Gamma \vdash^{-} A_1 =_\beta B_1 : K$. By the induction hypothesis 2 and K-EQ-Sym, $\Gamma \vdash^{-} K'' =_\beta K$. By the induction hypothesis 3, $\Gamma \vdash^{-} A_1 =_\beta B_1 : K''$, and by T-EQ-Conv, $\Gamma \vdash^{-} A_1 =_\beta B_1 : K$.

5. SS-Inc By the induction hypothesis 3, $\Gamma \vdash A, B, C, D : K$, $\Gamma \vdash^{-} A =_\beta C : K$, $\Gamma \vdash^{-} B =_\beta D : K$, and $\Gamma \vdash^{-} K =_\beta K$. By S-Conv, $\Gamma \vdash^{-} A \leq C : K$ and $\Gamma \vdash^{-} D \leq B : K$, and, by the induction hypothesis 4, $\Gamma \vdash^{-} C \leq D : K$. Finally, by S-Trans, $\Gamma \vdash^{-} A \leq B : K$. □

In Section 5 we shall see how Soundness (Corollary 5.12) can be used together with this result to show the admissibility of the structural rules.

Definition 4.7 (*Parallel Type Substitution*) A *parallel type substitution* γ for Γ is an assignment of types to type variables in $\mathrm{dom}(\Gamma)$. We write $\gamma[X{:=}A]$ to extend γ to assign A to X, $\gamma(X)$ for the value of the assignment at a variable, and $A[\gamma]$ for the replacement of variables in A with the values in γ; the value of this is undefined if there is a variable in A not in $\mathrm{dom}(\gamma)$. We say that γ is a type substitution for Γ in Δ if $\Delta \vdash_S \gamma(X) \leq A[\gamma] : K'$, where $\Delta \vdash_S K[\gamma] \twoheadrightarrow_{\mathrm{n}} K'$, for each X with $\Gamma = \Gamma_1, X{\leq}A : K, \Gamma_2$. A *renaming* is a parallel type substitution of variables for variables.

Lemma 4.8 (*Renaming*) If $\Gamma \vdash_S J$ and δ is a renaming for Γ in Δ then $\Delta \vdash_S J[\delta]$.

Proof: By induction on derivations. □

We write $\vdash_S \Delta \geq \Gamma$ if $\Delta \vdash_S \mathrm{ok}$, $x{:}A \in \Gamma$ implies $x{:}A \in \Delta$, and $X{\leq}A{:}K \in \Gamma$ implies $X{\leq}A{:}K \in \Delta$. Thinning, which says that judgements are monotonic with respect to context extension, now follows as a corollary of Renaming taking δ to be the identity substitution.

Corollary 4.9 (*Thinning*) If $\Gamma \vdash_S J$ and $\vdash_S \Delta \geq \Gamma$ then $\Delta \vdash_S J$.

Lemma 4.10 (*Adequacy*)

- If $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$ then $K \twoheadrightarrow_{\beta_2} K'$.
- If $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$ then $A \twoheadrightarrow_{\beta_2} B \twoheadrightarrow_{\beta_2} C$.

We use parallel reduction [19, 20] as a tool for proving subject reduction for the typed operational semantics.

Definition 4.11 (*Parallel Reduction*) Parallel reduction $\Rightarrow$ is the least relation over types and kinds defined by the following rules of inference.

$$X \Rightarrow X \qquad \text{(P-Var)}$$

$$\frac{A \Rightarrow A' \qquad K \Rightarrow K' \qquad B \Rightarrow B'}{\Lambda X{\leq}A{:}K.B \Rightarrow \Lambda X{\leq}A'{:}K'.B'} \tag{P-Lambda}$$

$$\frac{A \Rightarrow A' \qquad B \Rightarrow B'}{A\,B \Rightarrow A'\,B'} \tag{P-App}$$

$$\frac{A \Rightarrow A' \qquad B \Rightarrow B'}{(\Lambda X{\leq}C{:}K.A)(B) \Rightarrow A'[X{\leftarrow}B']} \tag{P-Beta}$$

plus similar rules, allowing reduction on each of the subterms, for the other type and kind formers.

Parallel reduction extends in the obvious way to contexts.

Parallel reduction is useful because it is closed under the following rule of substitution:

$$\frac{A \Rightarrow A' \qquad B \Rightarrow B'}{A[X{\leftarrow}B] \Rightarrow A'[X{\leftarrow}B']} \tag{P-Subst}$$

The following proof uses this and other simple properties about parallel reduction. See Takahashi's excellent account of parallel reduction [24] for more details.

Lemma 4.12 (*Parallel Subject Reduction for Types and Kinds*) If $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K, \Gamma \Rightarrow \Gamma'$ and $A \Rightarrow A'$, then there is a B' such that $B \Rightarrow B'$ and $\Gamma' \vdash_S A' \twoheadrightarrow_{\mathrm{w}} B' \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$.

Proof: By induction on derivations. We consider several cases:

ST-TVar Suppose $\Gamma \Rightarrow \Gamma'$ and $X \Rightarrow B$. By inversion $B \equiv X$. Also, clearly if $(X \leq A : K) \in \Gamma$ then $\Gamma \Rightarrow \Gamma'$ implies $A \Rightarrow A'$, $K \Rightarrow K''$ and $(X \leq A' : K') \in \Gamma'$. Hence, by inductive hypothesis $\Gamma' \vdash_S A' : K'$ and $\Gamma' \vdash_S K'' \twoheadrightarrow_{\mathrm{n}} K'$, so $\Gamma' \vdash_S X \twoheadrightarrow_{\mathrm{w}} X \twoheadrightarrow_{\mathrm{n}} X : K'$.

ST-TApp Suppose $\Gamma \Rightarrow \Gamma'$ and $A\,B \Rightarrow E$. Clearly if D is not an abstraction then A is not an abstraction, so by inversion $E \equiv A'\,B'$ with $A \Rightarrow A'$ and $B \Rightarrow B'$. Hence, by inductive hypothesis there is a D' such that $\Gamma' \vdash_S A' \twoheadrightarrow_{\mathrm{w}} D' \twoheadrightarrow_{\mathrm{n}} D : \Pi X{\leq}C{:}K_1.K_2$ and $D \Rightarrow D'$, and because D is not an abstraction and D is weak head normal then D' is not an abstraction; there is an E' such that $\Gamma' \vdash_S B' \twoheadrightarrow_{\mathrm{w}} E' \twoheadrightarrow_{\mathrm{n}} F : K_1$ and $E \Rightarrow E'$; $\Gamma' \vdash_S K_2[X{\leftarrow}B'] \twoheadrightarrow_{\mathrm{n}} K$; and $\Gamma' \vdash_S E' \leq_W C : K_1$. Hence, $\Gamma' \vdash_S A'\,B' \twoheadrightarrow_{\mathrm{w}} D'\,F \twoheadrightarrow_{\mathrm{n}} D'\,F$ by ST-TApp.

ST-Beta Suppose $\Gamma \Rightarrow \Gamma'$ and $B\,C \Rightarrow G$. By inversion of the reduction:

- $B \Rightarrow B'$, $C \Rightarrow C'$, and $G \equiv B'\,C'$. Then by inductive hypothesis $\Gamma' \vdash_S B' \twoheadrightarrow_{\mathrm{w}} \Lambda X{\leq}A''{:}K_1''.D' : \Pi X{\leq}A'{:}K_1'.K_2$ with $\Lambda X{\leq}A{:}K_1.D \Rightarrow \Lambda X{\leq}A''{:}K_1''.D'$, and also $\Gamma' \vdash_S C' \leq A'' : K_1'$, $\Gamma' \vdash_S K_2[X{\leftarrow}C'] \twoheadrightarrow_{\mathrm{n}} K$, and there is an E' such that $\Gamma' \vdash_S D'[X{\leftarrow}C'] \twoheadrightarrow_{\mathrm{w}} E' \twoheadrightarrow_{\mathrm{n}} F : K$ and $E \Rightarrow E'$. Hence $\Gamma' \vdash_S B'\,C' \twoheadrightarrow_{\mathrm{w}} E' \twoheadrightarrow_{\mathrm{n}} F : K$ with $E \Rightarrow E'$.
- $B \equiv \Lambda X{\leq}H{:}K_3.I$, $I \Rightarrow I'$, $C \Rightarrow C'$ and $B\,C \Rightarrow I'[X{\leftarrow}C']$. By inversion of the premise for B we know that $H \equiv A$, $K_3 \equiv K_1$ and $I \equiv D$. Hence $D \Rightarrow D'$ and $C \Rightarrow C'$ imply $D[X{\leftarrow}C] \Rightarrow D'[X{\leftarrow}C']$, so by inductive hypothesis there is an E' such that $\Gamma' \vdash_S D'[X{\leftarrow}C'] \twoheadrightarrow_{\mathrm{w}} E' \twoheadrightarrow_{\mathrm{n}} F : K$ and $E \Rightarrow E'$.

SWS-Refl By Lemma 4.3 and the definition of weak head normal, $X(A_1, \ldots, A_m)$ is normal. Hence, $X(A_1, \ldots, A_m) \Rightarrow C$ implies $C \equiv X(A_1, \ldots, A_m)$, and by inductive hypothesis $\Gamma \Rightarrow \Gamma'$ implies $\Gamma' \vdash_S X(A_1, \ldots, A_m) \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} B : K$. Hence, $\Gamma' \vdash_S C \leq_W D : K$ if $X(A_1, \ldots, A_m) \Rightarrow C$ and $X(A_1, \ldots, A_m) \Rightarrow D$. □

It is easy to show that $\rightarrow_\beta$ is included in $\Rightarrow$, and that $\Rightarrow$ is included in $\twoheadrightarrow_\beta$, so we have the following corollary:

COROLLARY 4.13 (*Subject Reduction for Types and Kinds*)

- If $\Gamma \vdash_S \mathrm{ok}$ and $\Gamma \rightarrow_\beta \Gamma'$ then $\Gamma' \vdash_S \mathrm{ok}$.
- If $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$ and $A \rightarrow_\beta A'$ then there is a B' such that $B \twoheadrightarrow_\beta B'$ and $\Gamma \vdash_S A' \twoheadrightarrow_{\mathrm{w}} B' \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$.
- If $\Gamma \vdash_S A \leq B : K$, $A \rightarrow_\beta A'$ and $B \rightarrow_\beta B'$ then $\Gamma \vdash_S A' \leq B' : K$.

Notice that this corollary incorporates both Subject Reduction and Church–Rosser, because the normal form is preserved by any one-step reduction.

We now prove Strong Normalization, using Subject Reduction to help.

DEFINITION 4.14 (*Strong Normalization*) Strong normalization for types, written $\mathrm{SN}(A)$, is the least relation closed under the following rule of inference:

$$\frac{\text{for all } B.(A \rightarrow_{\beta_2} B) \implies \mathrm{SN}(B)}{\mathrm{SN}(A)} \qquad \text{(SN-I)}$$

and similarly for kinds.

Strong normalization is easily seen to be closed under $\rightarrow_{\beta_2}$-reduction.

LEMMA 4.15 (*Strong Normalization for Types and Kinds*)

1. If $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K$ then A is strongly normalizing.
2. If $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$ then K is strongly normalizing.

PROOF: By induction on derivations.

ST-$\star$ By SN-I we need to show that if $\star \rightarrow_{\beta_2} K'$ then $\mathrm{SN}(K')$, which follows because $\star \rightarrow_{\beta_2} K'$ is impossible.

ST-Π By inductive hypothesis we know that $\mathrm{SN}(A)$, $\mathrm{SN}(K_1)$ and $\mathrm{SN}(K_2)$. By induction on these premises we show that $\mathrm{SN}(\Pi X{\leq}A{:}K_1.K_2)$. By SN-I we need to show that if $\Pi X{\leq}A{:}K_1.K_2 \rightarrow_{\beta_2} K'$ then $\mathrm{SN}(K')$. There are three possible reductions, corresponding to the subterms of $\Pi X{\leq}A{:}K_1.K_2$, and each of these cases follows by the appropriate inductive hypothesis.

ST-TOP By SN-I and the impossibility of $\mathrm{T}_\star \rightarrow_{\beta_2} B$.

ST-TVAR By SN-I and the impossibility of $X \rightarrow_{\beta_2} B$.

ST-TAPP By inductive hypothesis we know that $\mathrm{SN}(A)$ and $\mathrm{SN}(B)$. By induction on these we show that if $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} D : \Pi X{\leq}C{:}K_1.K_2$ and D is not an abstraction then $\mathrm{SN}(A\,B)$. By SN-I we need to show that if $A\,B \rightarrow_{\beta_2} G$ then $\mathrm{SN}(G)$. Again, if D is not an abstraction then A is not an abstraction, so if $A\,B \rightarrow_{\beta_2} G$ then we have two cases:

- $A \to_{\beta_2} A'$. Then by Subject Reduction (Lemma 4.13) there is a D' such that $\Gamma \vdash_S A' \twoheadrightarrow_{\mathrm{w}} D' : \Pi X{\leq}C{:}K_1.K_2$ and $D \Rightarrow D'$. Clearly if $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} D : \Pi X{\leq}C{:}K_1.K_2$, D is not an abstraction and $D \Rightarrow D'$ then D' is not an abstraction. Hence, by inductive hypothesis we know $\mathrm{SN}(A'\,B)$.
- $B \to_{\beta_2} B'$. This follows directly by inductive hypothesis.

ST-Arrow By inductive hypothesis we know $\mathrm{SN}(A_1)$ and $\mathrm{SN}(A_2)$. By induction on these we show $\mathrm{SN}(A_1{\to}A_2)$. By SN-I we need to show that if $A_1{\to}A_2 \to_{\beta_2} C$ then $\mathrm{SN}(C)$. By inversion either $A_1 \to_{\beta_2} C_1$ or $A_2 \to_{\beta_2} C_2$, and each case follows by the inductive hypothesis.

ST-TAll Similar to the case for ST-Π.

ST-TAbs Similar to the case for ST-Π.

ST-Beta By inductive hypothesis we know that $\mathrm{SN}(B)$, $\mathrm{SN}(C)$, and $\mathrm{SN}(D[X{\leftarrow}C])$. By induction on $\mathrm{SN}(B)$ and $\mathrm{SN}(C)$ we show that $\Gamma \vdash_S B \twoheadrightarrow_{\mathrm{w}} \Lambda X{\leq}A{:}K_1.D : \Pi X{\leq}A'{:}K_1'.K_2$ and $\mathrm{SN}(D[X{\leftarrow}C])$ imply $\mathrm{SN}(B\,C)$. By SN-I, we need $B\,C \to_{\beta_2} G$ implies $\mathrm{SN}(G)$. By inversion of $B\,C \to_{\beta_2} G$ there are three cases:

- $B \to_{\beta_2} B'$. Then by Subject Reduction (Lemma 4.13) there is an H such that $\Gamma \vdash_S B' \twoheadrightarrow_{\mathrm{w}} H : \Pi X{\leq}A'{:}K_1'.K_2$ and $\Lambda X{\leq}A{:}K_1.D \Rightarrow H$. By inversion $H \equiv \Lambda X{\leq}A''{:}K_1''.D'$ with $A \Rightarrow A''$, $K_1 \Rightarrow K_1''$ and $D \Rightarrow D'$. Because SN is closed under reduction we know $\mathrm{SN}(D'[X{\leftarrow}C])$. Hence $\mathrm{SN}(B'\,C)$ by inductive hypothesis.
- $C \to_{\beta_2} C'$. Then since SN is closed under reduction $\mathrm{SN}(D[X{\leftarrow}C'])$, so by inductive hypothesis $\mathrm{SN}(B\,C')$.
- $B \equiv \Lambda X{\leq}A''{:}K_1''.H$ and $B\,C \to_{\beta_2} H[X{\leftarrow}C]$. By inversion of $\Gamma \vdash_S B \twoheadrightarrow_{\mathrm{w}} \Lambda X{\leq}A{:}K_1.D : \Pi X{\leq}A'{:}K_1'.K_2$ we know that $B \equiv \Lambda X{\leq}A{:}K_1.D$, so in particular $H \equiv D$. Hence $\mathrm{SN}(H[X{\leftarrow}C])$ follows by assumption. □

Definition 4.16 We define conversion of contexts, written $\vdash_S \Gamma;\Delta \twoheadrightarrow_{\mathrm{n}} \Phi$, as the least relation closed under the following rules of inference:

$$\vdash_S \emptyset;\emptyset \twoheadrightarrow_{\mathrm{n}} \emptyset \qquad \text{(SCN-Empty)}$$

$$\frac{\vdash_S \Gamma;\Delta \twoheadrightarrow_{\mathrm{n}} \Phi \qquad \Gamma \vdash_S A, B \twoheadrightarrow_{\mathrm{n}} C : \star \qquad x \notin \mathrm{dom}(\Gamma)}{\vdash_S \Gamma,\, x{:}A;\Delta,\, x{:}B \twoheadrightarrow_{\mathrm{n}} \Phi,\, x{:}C} \qquad \text{(SCN-Var)}$$

$$\frac{\vdash_S \Gamma;\Delta \twoheadrightarrow_{\mathrm{n}} \Phi \qquad \Gamma \vdash_S K, K' \twoheadrightarrow_{\mathrm{n}} K'' \qquad \Gamma \vdash_S A, B \twoheadrightarrow_{\mathrm{n}} C : K'' \quad X \notin \mathrm{dom}(\Gamma)}{\vdash_S \Gamma,\, X{\leq}A{:}K;\Delta,\, X{\leq}B{:}K' \twoheadrightarrow_{\mathrm{n}} \Phi,\, X{\leq}C{:}K''} \qquad \text{(SCN-TVar)}$$

Lemma 4.17 (*Context Conversion*) If $\vdash_S \Gamma,\Delta \twoheadrightarrow_{\mathrm{n}} \Phi$ and $\Gamma \vdash_S J$ then $\Delta \vdash_S J$.

Proof: By induction on derivations. We consider two representative cases:

ST-TVar We know that $(X{\leq}A : K) \in \Gamma$, so by inversion of $\Gamma;\Delta \twoheadrightarrow_{\mathrm{n}} \Phi$ we know that there are Γ_0, Γ_1, Δ_0 and Δ_1 such that $\Gamma \equiv \Gamma_0, X{\leq}A : K, \Gamma_1$ and $\Delta \equiv \Delta_0, X{\leq}B : K'', \Delta_1$, where $\Gamma_0 \vdash_S A \twoheadrightarrow_{\mathrm{n}} C : K'''$, $\Gamma_0 \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'''$, $\Delta_0 \vdash_S B \twoheadrightarrow_{\mathrm{n}} C : K'''$, and $\Delta_0 \vdash_S K'' \twoheadrightarrow_{\mathrm{n}} K'''$. By Renaming $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'''$, $\Delta \vdash_S K'' \twoheadrightarrow_{\mathrm{n}} K'''$, and $\Delta \vdash_S B \twoheadrightarrow_{\mathrm{n}} C : K'''$. We have a premise that $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$, so by Determinacy $K' \equiv K'''$, so $\Delta \vdash_S X \twoheadrightarrow_{\mathrm{w}} X \twoheadrightarrow_{\mathrm{n}} X : K'$.

ST-TAbs By inductive hypothesis $\Delta \vdash_S A \twoheadrightarrow_{\mathrm{n}} C : K_1'$ and $\Delta \vdash_S K_1 \twoheadrightarrow_{\mathrm{n}} K_1'$. Hence $\vdash_S \Gamma, X{\leq}A : K_1; \Delta, X{\leq}B : K_1 \twoheadrightarrow_{\mathrm{n}} \Phi, X{\leq}C : K_1'$, and so by inductive hypothesis $\Delta, X{\leq}A : K_1 \vdash_S B \twoheadrightarrow_{\mathrm{n}} D : K_2$. The result follows by ST-TAbs. □

Lemma 4.18 (*Subtyping Conversion*)

- Suppose that $\Gamma \vdash_S A \leq_W B : K$. Then:
  - If $\Gamma \vdash_S A, A' \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} C : K$ then $\Gamma \vdash_S A' \leq_W B : K$.
  - If $\Gamma \vdash_S B, B' \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} C : K$ then $\Gamma \vdash_S A \leq_W B' : K$.
- Suppose that $\Gamma \vdash_S A \leq B : K$. Then:
  - If $\Gamma \vdash_S A, A' \twoheadrightarrow_{\mathrm{n}} C : K$ then $\Gamma \vdash_S A' \leq B : K$.
  - If $\Gamma \vdash_S B, B' \twoheadrightarrow_{\mathrm{n}} C : K$ then $\Gamma \vdash_S A \leq B' : K$.

Proof: By induction on derivations. We show two interesting cases:

SWS-All We consider the case that $\Gamma \vdash_S \forall X{\leq}A_1{:}K.A_2, A' \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} D : \star$, where the other case is similar but simpler. By inversion on the derivation for $\forall X{\leq}A_1{:}K.A_2$ we know that $D \equiv \forall X{\leq}C_1{:}K'''.C_2$ with $\Gamma \vdash_S A_1 \twoheadrightarrow_{\mathrm{n}} C_1 : K'''$, $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'''$ and $\Gamma, X{\leq}A_1 : K \vdash_S A_2 \twoheadrightarrow_{\mathrm{n}} C_2 : \star$. By Determinacy $K'' \equiv K'''$ and $C \equiv C_1$. By inversion on the derivation that $\Gamma \vdash_S A' \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} \forall X{\leq}C_1{:}K'''.C_2 : \star$ we know that $A' \equiv \forall X{\leq}A_1'{:}K''''.A_2'$, $\Gamma \vdash_S A_1' \twoheadrightarrow_{\mathrm{n}} C_1 : K''$, $\Gamma \vdash_S K'''' \twoheadrightarrow_{\mathrm{n}} K''$ and $\Gamma, X{\leq}A_1' : K'''' \vdash_S A_2' \twoheadrightarrow_{\mathrm{n}} C_2 : \star$. By Context Conversion we know that $\Gamma, X{\leq}A_1 : K \vdash_S A_2' \twoheadrightarrow_{\mathrm{n}} C_2 : \star$, so by inductive hypothesis $\Gamma, X{\leq}A_1 : K \vdash_S A_2' \leq B_2 : \star$. Finally, by Context Conversion again $\Gamma, X{\leq}A_1' : K'''' \vdash_S A_2' \leq B_2 : \star$, and the result follows by SWS-All.

SS-Inc We consider the case that $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} C' \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} E : K$ and $\Gamma \vdash_S A' \twoheadrightarrow_{\mathrm{w}} C'' \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} E : K$, where the other case is similar. We know $C \equiv C'$ by Determinacy. Furthermore, by Adequacy and Subject Reduction $\Gamma \vdash_S C, C'' \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} E : K$, so by inductive hypothesis $\Gamma \vdash_S C'' \leq_W D : K$. Hence $\Gamma \vdash_S A' \leq B : K$ by SS-Inc. □

Lemma 4.19 If $\Gamma \vdash_S A \leq_W B : K$ then there is a C such that $\Gamma \vdash_S A \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} C : K$.

Proof: By inversion of $\Gamma \vdash_S A \leq_W B : K$, also using inversion on the premises for SWS-Arrow, SWS-All and SWS-TAbs. □

Lemma 4.20 (*Reflexivity*) If $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{n}} B : K$ then $\Gamma \vdash_S A \leq A : K$.

Proof: We show the stronger property, that if $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\twoheadrightarrow_{\mathrm{n}} C : K$ then $\Gamma \vdash_S B \leq_W B : K$ and $\Gamma \vdash_S A \leq A : K$, by induction on derivations. □

Lemma 4.21 (*Transitivity*) If $\Gamma \vdash_S A \leq B : K$ and $\Gamma \vdash_S B \leq C : K$ then $\Gamma \vdash_S A \leq C : K$.

Proof: We show the stronger property that:

- if $\Gamma \vdash_S B \leq C : K$ then:
  1. if $\Gamma \vdash_S A \leq B : K$ then $\Gamma \vdash_S A \leq C : K$, and

2. if $\Gamma \vdash_S C \leq D : K$ then $\Gamma \vdash_S B \leq D : K$, and

- if $\Gamma \vdash_S B \leq_W C : K$ then:

1. if $\Gamma \vdash_S A \leq_W B : K$ then $\Gamma \vdash_S A \leq_W C : K$, and
2. if $\Gamma \vdash_S C \leq_W D : K$ then $\Gamma \vdash_S B \leq_W D : K$.

by induction on derivations. We show several cases:

SWS-Top Case 1 follows by Lemma 4.19 and SWS-Top, and Case 2 follows by inversion on derivations such that $\Gamma \vdash_S \mathrm{T}_\star \leq_W D : \star$.

SWS-Arrow

1. Suppose $\Gamma \vdash_S C \leq_W A_1 \to A_2 : \star$. By induction on this we show that $\Gamma \vdash_S C \leq_W B_1 \to B_2 : \star$.

   SWS-TApp By the second inductive hypothesis and SWS-TApp.

   SWS-Arrow We have that $C \equiv C_1 \to C_2$ and that $\Gamma \vdash_S C \leq_W A_1 \to A_2 : \star$ by $\Gamma \vdash_S A_1 \leq C_1 : \star$ and $\Gamma \vdash_S C_2 \leq A_2 : \star$. By the first inductive hypothesis Case 2 $\Gamma \vdash_S B_1 \leq C_1 : \star$, and by the first inductive hypothesis Case 1 $\Gamma \vdash_S C_2 \leq B_2 : \star$. Hence $\Gamma \vdash_S C_1 \to C_2 \leq_W B_1 \to B_2 : \star$ by SWS-Arrow.

2. Suppose $\Gamma \vdash_S B_1 \to B_2 \leq_W C : \star$. By inversion on this we show that $\Gamma \vdash_S A_1 \to A_2 \leq_W C : \star$.

   SWS-Top Then $\Gamma \vdash_S A_1 \to A_2 \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} D : \star$ by Lemma 4.19, so $\Gamma \vdash_S A_1 \to A_2 \leq_W \mathrm{T}_\star : \star$ by SWS-Top.

   SWS-Arrow We know that $\Gamma \vdash_S C_1 \leq B_1 : \star$ and $\Gamma \vdash_S B_2 \leq C_2 : \star$. Hence by inductive hypothesis Case 1 $\Gamma \vdash_S C_1 \leq A_1 : \star$, and by the first inductive hypothesis Case 2 $\Gamma \vdash_S A_2 \leq C_2 : \star$, and so $\Gamma \vdash_S A_1 \to A_2 \leq_W C_1 \to C_2 : \star$ by SWS-Arrow.

SS-Inc Both cases follow by inversion of the assumption, Determinacy, the appropriate inductive hypothesis for $\leq_W$ and SS-Inc. □

4.2 Basic Properties For $\mathcal{F}^{\omega}_{\leq}$

Lemma 4.22 If $\Gamma \vdash \mathrm{ok}$ then all variables in $\mathrm{dom}(\Gamma)$ are different.

Proof: By induction on the structure of Γ. □

Lemma 4.23 If $\Gamma \vdash J$ and Γ' is a prefix of Γ, then $\Gamma' \vdash \mathrm{ok}$.

Proof: By induction on the derivation of $\Gamma \vdash J$. □

Lemma 4.24 (*Strengthening*) If $\Gamma_1, y{:}C, \Gamma_2 \vdash J$ and $y \notin \mathrm{FV}(J)$ then $\Gamma_1, \Gamma_2 \vdash J$.

Proof: By induction on the derivation of $\Gamma_1, y{:}C, \Gamma_2 \vdash J$. Most cases follow by the induction hypothesis and the corresponding rule, and C-Var uses Lemma 4.23. □

Lemma 4.25 If $Y \notin \mathrm{FV}(A)$ then $B[X \leftarrow C][Y \leftarrow A[X \leftarrow C]] = B[Y \leftarrow A][X \leftarrow C]$.

PROOF: By induction on the structure of B. □

LEMMA 4.26 (*Term Substitution*)

1. If $\Gamma_1, x{:}A, \Gamma_2 \vdash M : B$ and $\Gamma_1 \vdash N : A$ then $\Gamma_1, \Gamma_2 \vdash M[x \leftarrow N] : B$.
2. If $\Gamma_1, X \leq A{:}K, \Gamma_2 \vdash M : B$ and $\Gamma_1 \vdash C \leq A$ then $\Gamma_1, \Gamma_2[X \leftarrow C] \vdash M[X \leftarrow C] : B[X \leftarrow C]$.

PROOF:

1. By induction on derivations, where for T-VAR we use Weakening (Corollary 4.9) and Strengthening (Lemma 4.24), and for T-ABS we use Lemmas 4.23 and 4.22.
2. By induction on derivations, using Lemmas 4.23 and 4.22 in the case T-TABS; using Lemma 4.25 and the rule SUBST in the case T-TAPP; and using the rule SUBST in the case T-SUB. □

5 Soundness

In this section we show the most important result for the metatheory of $\mathcal{F}^{\omega}_{\leq}$: that the typed operational semantics is sound for the typing rules in Section 2. This proof is similar to traditional proofs of strong normalization, although it differs from many such proofs because it also needs to keep type information. Hence, we build a Kripke-style model following Coquand and Gallier [14], where the possible worlds are valid contexts Δ and ordering is lexicographic, written $\Delta' \geq \Delta$.

5.1 The Interpretation

We begin by defining the interpretation of kinds K with respect to a type substitution γ in a context Δ. There are two components to the interpretation: the first component is a set of types well-formed in Δ with particular properties, and models the judgement $\Gamma \vdash A : K$; the second component is a relation on types in the first component, and models the judgement $\Gamma \vdash A \leq B : K$. The properties that the interpretation satisfies include the usual saturated set conditions, properties about Kripke-style models such as monotonicity, the substitution property, and properties lifted from the typed operational semantics such as transitivity elimination.

Partial interpretations are common in defining the semantics of dependent type theories [16, 23]. In our proof, we need a partial interpretation to guarantee that the bound is normalizing for each Π-constructor. This is information that can only be known when the proof itself is carried out, not when we define the interpretation.

DEFINITION 5.1 (*Semantic Object*) A is a *semantic object* for Γ and K if $\Gamma \vdash_S A \leq \mathrm{T}_K : K$.

DEFINITION 5.2 (*Interpretation of Kinds*) We give a partial interpretation of kinds for both judgements, $[\![-]\!]_:(-,-)$ for typing and $[\![-]\!]_{\leq}(-,-)$ for subtyping:

- The interpretation $[\![\star]\!]\gamma\Delta$ is well-defined if $\Delta \vdash_S \mathrm{ok}$. The two components are:
  - $[\![\star]\!]_:\gamma\Delta = \{A \mid A \text{ is a semantic object for } \Delta \text{ and } \star\}$.

- $[\![\star]\!]_{\leq}\gamma\Delta = \{(A,B) \mid A \text{ and } B \text{ are semantic objects and } \Delta \vdash_S A \leq B : \star\}$.

- The interpretation $[\![\Pi X{\leq}A{:}K_1.K_2]\!]\gamma\Delta$ is well-defined if the following conditions hold:
  - there is a K' such that $\Delta \vdash_S (\Pi X{\leq}A{:}K_1.K_2)[\gamma] \twoheadrightarrow_{\mathrm{n}} K'$,
  - $[\![K_1]\!]\gamma\Delta'$ is defined for any $\vdash_S \Delta' \geq \Delta$, and
  - if $\vdash_S \Delta' \geq \Delta$ and $(C, A[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta'$, then $[\![K_2]\!]\gamma[X{:=}C]\Delta'$ is well-defined.

  Under these circumstances, the two components are:
  - $[\![\Pi X{\leq}A{:}K_1.K_2]\!]_{:}\gamma\Delta$ is the set of B such that:
    - B is a semantic object for Δ and K',
    - if $\vdash_S \Delta' \geq \Delta$ and $(C, A[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta'$, then $B\,C \in [\![K_2]\!]_{:}\gamma[X{:=}C]\Delta'$.
  - $[\![\Pi X{\leq}A{:}K_1.K_2]\!]_{\leq}\gamma\Delta$ is the set of (B,C) such that:
    - B and C are in $[\![\Pi X{\leq}A{:}K_1.K_2]\!]_{:}\gamma\Delta$,
    - $\Delta \vdash_S B \leq C : K'$,
    - if $\vdash_S \Delta' \geq \Delta$ and $(D, A[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta'$ then $(B\,D, C\,D) \in [\![K_2]\!]_{\leq}\gamma[X{:=}D]\Delta'$.

Definition 5.3 (*Interpretation of Contexts*) We define a partial interpretation of contexts:

- $[\![\emptyset]\!]\Delta = \{\epsilon\}$. This is defined if $\Delta \vdash_S \mathrm{ok}$.
- $[\![\Gamma, x{:}A]\!]\Delta = [\![\Gamma]\!]\Delta$. This is defined if $x \notin \mathrm{dom}(\Gamma)$ and, for any $\vdash_S \Delta' \geq \Delta$, $[\![\Gamma]\!]\Delta'$ is defined and $A[\gamma] \in [\![\star]\!]_{:}\gamma\Delta'$ for every $\gamma \in [\![\Gamma]\!]\Delta'$.
- $[\![\Gamma, X{\leq}A{:}K]\!]\Delta = \{\gamma[X{:=}B] \mid \gamma \in [\![\Gamma]\!]\Delta \text{ and } (B, A[\gamma]) \in [\![K]\!]_{\leq}\gamma\Delta\}$. This is defined if $X \notin \mathrm{dom}(\Gamma)$ and, for any $\vdash_S \Delta' \geq \Delta$, $[\![\Gamma]\!]\Delta'$ is defined and $A[\gamma] \in [\![K]\!]_{:}\gamma\Delta'$ for every $\gamma \in [\![\Gamma]\!]\Delta'$.

5.2 Properties of the Interpretation

We need to establish a variety of properties about the interpretation before carrying out the soundness proof.

Definition 5.4 We write $\Delta \vdash_S \gamma, \gamma' \twoheadrightarrow_{\mathrm{n}} \gamma''$ if for all $X \in \mathrm{dom}(\gamma)$ there is a K' such that $\Delta \vdash_S \gamma(X), \gamma'(X) \twoheadrightarrow_{\mathrm{n}} \gamma''(X) : K'$.

We first give some simple properties about the interpretation:

Lemma 5.5 (*Basic Properties*)

1. If $[\![K]\!]\gamma\Delta$ is defined then there is a K' such that $\Delta \vdash_S K[\gamma] \twoheadrightarrow_{\mathrm{n}} K'$.
2. If $\gamma \in [\![\Gamma]\!]\Delta$ then $\Delta \vdash_S \mathrm{ok}$.
3. If $[\![K]\!]\gamma\Delta$ is defined and $\gamma'(X) = \gamma(X)$ for all $X \in \mathrm{dom}(\gamma)$ then $[\![K]\!]\gamma\Delta = [\![K]\!]\gamma'\Delta$.
4. If $[\![K]\!]\gamma\Delta$ and $[\![K]\!]\gamma'\Delta$ are defined and $\Delta \vdash_S \gamma, \gamma' \twoheadrightarrow_{\mathrm{n}} \gamma''$ then $[\![K]\!]\gamma\Delta = [\![K]\!]\gamma'\Delta$.

PROOF: Properties 1 and 2 follow by straightforward induction on K and Γ.

Property 3 follows by induction on K, using the fact that $A[\gamma] \equiv A[\gamma']$ for types A if $\gamma(X) = \gamma'(X)$ for all $X \in \mathrm{FV}(A)$, and similarly for kinds.

Property 4 follows by induction on K using the fact that $\Delta \vdash_S K[\gamma], K[\gamma'] \twoheadrightarrow_{\mathrm{n}} K''$ if there is a γ'' such that for all $X \in \mathrm{FV}(A)$ there is a K''' such that $\Delta \vdash_S \gamma(X), \gamma'(X) \twoheadrightarrow_{\mathrm{n}} \gamma''(X) : K'''$, which follows using Subject Reduction and Determinacy. □

Next, we need some properties similar to the usual saturated set conditions. In the following we assume $\Delta \vdash_S K[\gamma] \twoheadrightarrow_{\mathrm{n}} K'$:

LEMMA 5.6 (*Saturated Sets*)

1. If $A \in [\![K]\!]_:\gamma\Delta$ then A is a semantic object for Δ and K'.
2. If $(A, B) \in [\![K]\!]_\leq\gamma\Delta$ then $\Delta \vdash_S A \leq B : K'$.
3. If $(A, B) \in [\![K]\!]_\leq\gamma\Delta$ then $A \in [\![K]\!]_:\gamma\Delta$ and $B \in [\![K]\!]_:\gamma\Delta$.
4. If A and B are in $[\![K]\!]_:\gamma\Delta$ and $\Delta \vdash_S A, B \twoheadrightarrow_{\mathrm{n}} C : K'$ then $(A, B) \in [\![K]\!]_\leq\gamma\Delta$.
5. If (A, B) and (B, C) are in $[\![K]\!]_\leq\gamma\Delta$ then $(A, C) \in [\![K]\!]_\leq\gamma\Delta$.
6. If $\Delta(X)(A_1, \ldots, A_m) \in [\![K]\!]_:\gamma\Delta$ then $(X(A_1, \ldots, A_m), \Delta(X)(A_1, \ldots, A_m)) \in [\![K]\!]_\leq\gamma\Delta$.
7. If $\Delta \vdash_S A, B \twoheadrightarrow_{\mathrm{w}} C \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} D : K'$, $A \in [\![K]\!]_:\gamma\Delta$ and B is a semantic object for Δ and K' then $B \in [\![K]\!]_:\gamma\Delta$.
8. If $A \in [\![K]\!]_:\gamma\Delta$ then $(A, \mathrm{T}_{K[\gamma]}) \in [\![K]\!]_\leq\gamma\Delta$.

PROOF: Properties 1, 2 and 3 follow by construction.

Property 4 follows by induction on K, using Reflexivity and Conversion of subtyping in the semantics, plus Adequacy, Subject Reduction and Determinism for the Π case.

Property 5 follows by induction on K, using Transitivity of subtyping in the semantics.

For Property 6, we first show a lemma stating that if $\Delta(X)(A_1, \ldots, A_m)$ is a semantic object for Δ and K' then $\Delta \vdash_S X(A_1, \ldots, A_m) \leq \Delta(X)(A_1, \ldots, A_m) : K'$, which follows by definition of $\Delta(X)$, Adequacy and Reflexivity for subtyping in the semantics. Hence $X(A_1, \ldots, A_m)$ is a semantic object for Δ and K', using this lemma and Transitivity for the semantics. Property 6 then follows by induction on K, using Properties 1 and 3, and the fact that if $\vdash_S \Delta' \geq \Delta$ then $\Delta'(X) = \Delta(X)$ for all $X \in \mathrm{dom}(\Delta)$.

For Property 7, first notice that if $\Delta \vdash_S A, B \twoheadrightarrow_{\mathrm{w}} C \twoheadrightarrow_{\mathrm{n}} D : K'$ and A is a semantic object for Δ and K' then B is a semantic object for Δ and K' as well, using Determinism to show that $\Delta \vdash_S B \leq \mathrm{T}'_K : K'$. Furthermore, we can show that if $\Delta \vdash_S A, B \twoheadrightarrow_{\mathrm{w}} C \twoheadrightarrow_{\mathrm{n}} D : K$ and $\Delta \vdash_S A\,E \twoheadrightarrow_{\mathrm{w}} F \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} G : K'$ then $\Delta \vdash_S B\,E \twoheadrightarrow_{\mathrm{w}} F \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} G : K'$. The result follows by induction on K, using Thinning and this simple lemma in the Π case.

Finally, for Property 8, we first observe that if $\Delta \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$ then T_K is a semantic object for Δ and K', which follows by a simple induction on K. The result follows by induction on K, using Properties 3, 4 and 5, plus Thinning and Conversion of subtyping. □

We also need properties corresponding to the model being a Kripke-model:

LEMMA 5.7 (*Monotonicity*) If $\vdash_S \Delta' \geq \Delta$ then:

1. $A \in [\![K]\!]_:\gamma\Delta$ implies $A \in [\![K]\!]_:\gamma\Delta'$.

2. $(A, B) \in [\![K]\!]_{:\gamma\Delta}$ implies $(A, B) \in [\![K]\!]_{\leq\gamma\Delta'}$.

3. $\gamma \in [\![\Gamma]\!]\Delta$ implies $\gamma \in [\![\Gamma]\!]\Delta'$.

PROOF: By induction on K or Γ, using Thinning for the first two and using the first two for the last. □

We also need to account for the dependency, since bounds in kinds include types:

LEMMA 5.8 (*Substitution*)

1. $[\![K]\!]\gamma_1[X{:=}B[\gamma_1]]\gamma_2\Delta = [\![K[X{\leftarrow}B]]\!]\gamma_1\gamma_2$.

2. Suppose that:

   - $[\![\Gamma_1,\ X{\leq}B{:}K,\ \Gamma_2]\!]\Delta$ is defined, and
   - $(A[\gamma_1], B[\gamma_1]) \in [\![K]\!]\gamma_1\Delta$ for $\gamma_1 \in [\![\Gamma_1]\!]\Delta$.

   Then:

   - $[\![\Gamma_1,\ \Gamma_2[X{\leftarrow}A]]\!]\Delta$ is defined, and
   - if $\gamma_1\gamma_2 \in [\![\Gamma_1,\ \Gamma_2[X{\leftarrow}A]]\!]\Delta$ then $\gamma_1[X{:=}A[\gamma_1]]\gamma_2 \in [\![\Gamma_1,\ X{\leq}B{:}K,\ \Gamma_2]\!]\Delta$.

PROOF: Case 1 follows by induction on K, using basic properties of parallel substitution. Case 2 follows by induction on Γ_2, using basic properties of parallel substitution and Case 1. □

Finally, we prove a lemma to deal with the rules of context equality.

LEMMA 5.9 (*Context Replacement*) Suppose:

- $[\![\Gamma_1,\ X{\leq}A{:}K,\ \Gamma_2]\!]\Delta$ is defined, and
- for any $\gamma_1 \in [\![\Gamma_1]\!]\Delta$ then:
  - $\Delta \vdash_S K[\gamma_1], K'[\gamma_1] \twoheadrightarrow_{\mathrm{n}} K''$ and $\Delta \vdash_S A[\gamma_1], B[\gamma_1] \twoheadrightarrow_{\mathrm{n}} C : K''$,
  - $[\![K]\!]\gamma_1\Delta = [\![K']\!]\gamma_1\Delta$, and
  - $A[\gamma_1] \in [\![K]\!]_{:\gamma_1\Delta}$ and $B[\gamma_1] \in [\![K']\!]_{:\gamma_1\Delta}$.

Then $[\![\Gamma_1,\ X{\leq}A{:}K,\ \Gamma_2]\!]\Delta = [\![\Gamma_1,\ X{\leq}B{:}K',\ \Gamma_2]\!]\Delta$.

PROOF: By induction on Γ_1, using Lemma 5.6 Case 4 for the base case. □

5.3 Soundness

We can now prove soundness. As usual for strong normalization proofs, we first need to prove the more general statement with respect to arbitrary well-behaved substitutions.

THEOREM 5.10 If $\Gamma \vdash J$ and $\Delta \vdash_S$ ok then $[\![\Gamma]\!]\Delta$ is defined. Furthermore:

1. If $\Gamma \vdash K$ and $\gamma \in [\![\Gamma]\!]\Delta$ then $[\![K]\!]\gamma\Delta$ is defined.

2. If $\Gamma \vdash A : K$ and $\gamma \in [\![\Gamma]\!]\Delta$ then $A[\gamma] \in [\![K]\!]_{:\gamma\Delta}$.

3. If $\Gamma \vdash K = K'$ and $\gamma \in [\![\Gamma]\!]\Delta$ then $[\![K]\!]\gamma\Delta = [\![K']\!]\gamma\Delta$ and there is a K'' such that $\Delta \vdash_S K[\gamma], K'[\gamma] \twoheadrightarrow_{\mathrm{n}} K''$.

4. If $\Gamma \vdash A = B : K$ and $\gamma \in [\![\Gamma]\!]\Delta$ then $A[\gamma]$ and $B[\gamma]$ are in $[\![K]\!]_{\leq}\gamma\Delta$ and there are C and K' such that $\Delta \vdash_S K[\gamma] \twoheadrightarrow_{\mathrm{n}} K'$ and $\Delta \vdash_S A[\gamma], B[\gamma] \twoheadrightarrow_{\mathrm{n}} C : K'$.

5. If $\Gamma \vdash A \leq B : K$ and $\gamma \in [\![\Gamma]\!]\Delta$ then $(A[\gamma], B[\gamma]) \in [\![K]\!]_{\leq}\gamma\Delta$.

PROOF: By induction on derivations, using the above properties about the interpretation. We consider several cases:

C-EMPTY By definition $[\![\emptyset]\!]\Delta$ is defined if $\Delta \vdash_S \mathrm{ok}$.

C-VAR By inductive hypothesis $[\![\Gamma]\!]\Delta'$ is defined for $\vdash_S \Delta' \geq \Delta$. If $\gamma \in [\![\Gamma]\!]\Delta'$, then $A[\gamma] \in [\![\star]\!]_{\cdot}\gamma\Delta'$ by inductive hypothesis. Furthermore, $x \notin \mathrm{dom}(\Gamma)$, so $[\![\Gamma,\, x{:}A]\!]\Delta$ is defined.

C-TVAR By inductive hypothesis $[\![\Gamma]\!]\Delta'$ is defined for $\vdash_S \Delta' \geq \Delta$. If $\gamma \in [\![\Gamma]\!]\Delta'$, then $A[\gamma] \in [\![K]\!]_{\cdot}\gamma\Delta'$ by inductive hypothesis, and $X \notin \mathrm{dom}(\Gamma)$, so $[\![\Gamma,\, X{\leq}A{:}K]\!]\Delta$ is defined.

KIND AGREEMENT By inductive hypothesis $[\![\Gamma]\!]\Delta$ is defined.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. By inductive hypothesis $A[\gamma] \in [\![K]\!]_{\cdot}\gamma\Delta$, so $[\![K]\!]_{\cdot}\gamma\Delta$ is defined. Furthermore, by Lemma 5.5 Case 1 there is a K' such that $\Delta \vdash_S K[\gamma] \twoheadrightarrow_{\mathrm{n}} K'$.

K-SUBST By inductive hypothesis $[\![\Gamma_1,\, X{\leq}B{:}K,\, \Gamma_2]\!]\Delta$ and $[\![\Gamma_0]\!]\Delta$ are defined, and $\gamma_0 \in [\![\Gamma_0]\!]\Delta$ implies $(A[\gamma_0], B[\gamma_0]) \in [\![K]\!]_{\leq}\gamma_0\Delta$. By Lemma 5.8 Case 2 $[\![\Gamma_1,\, \Gamma_2[X{\leftarrow}A]]\!]\Delta$ is defined.

Furthermore, $\gamma_0\gamma_1 \in [\![\Gamma_1,\, \Gamma_2[X{\leftarrow}A]]\!]\Delta$ implies $\gamma_0[X{:=}A[\gamma_0]]\gamma_1 \in [\![\Gamma_1,\, X{\leq}A{:}K',\, \Gamma_2]\!]\Delta$, so $[\![K]\!]\gamma_0[X{:=}A[\gamma_0]]\gamma_1\Delta$ is defined by inductive hypothesis, and $[\![K]\!]\gamma_0[X{:=}A[\gamma_0]]\gamma_1\Delta = [\![K[X{\leftarrow}A]]\!]\gamma_0\gamma_1\Delta$ by Lemma 5.8 Case 1.

K-CTXT-EQ The inductive hypotheses satisfy the premises of Lemma 5.9, so

$$[\![\Gamma_1,\, X{\leq}A{:}K,\, \Gamma_2]\!]\Delta \;=\; [\![\Gamma_1,\, X{\leq}B{:}K',\, \Gamma_2]\!]\Delta$$

Hence, $[\![\Gamma_1,\, X{\leq}B{:}K',\, \Gamma_2]\!]\Delta$ is defined, and if $\gamma \in [\![\Gamma_1,\, X{\leq}B{:}K',\, \Gamma_2]\!]\Delta$ then $\gamma \in [\![\Gamma_1,\, X{\leq}A{:}K,\, \Gamma_2]\!]\Delta$, so by inductive hypothesis $[\![K]\!]\gamma\Delta$ is defined.

T-TOP By inductive hypothesis $[\![\Gamma]\!]\Delta$ is defined.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. We know $\Delta \vdash_S \mathrm{ok}$ by Lemma 5.5 Case 2. Hence $\Delta \vdash_S \mathrm{T}_\star \twoheadrightarrow_{\mathrm{n}} \mathrm{T}_\star : \star$ by ST-TOP, and $\Delta \vdash_S \mathrm{T}_\star \leq_W \mathrm{T}_\star : \star$ by SWS-TOP and SS-INC. Hence $\mathrm{T}_\star$ is a semantic object for Δ and $\star$, and so $\mathrm{T}_\star \in [\![\star]\!]_{\cdot}\gamma\Delta$.

T-TVAR By inductive hypothesis $[\![\Gamma_1, X \leq A : K, \Gamma_2]\!]\Delta$ is defined.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. Then $\gamma = \gamma_1[X{:=}B]\gamma_2$, with $\gamma_1 \in [\![\Gamma_1]\!]\Delta$ and $(B, A[\gamma_1]) \in [\![K]\!]_{\leq}\gamma_1\Delta$, by definition of $[\![\Gamma]\!]\Delta$. Hence $B \in [\![K]\!]_{\cdot}\gamma_1\Delta$ by Lemma 5.6 Case 3, and $B \in [\![K]\!]_{\cdot}\gamma\Delta$ by Lemma 5.5 Case 3.

T-TABS By inductive hypothesis $[\![\Gamma,\, X{\leq}A_1{:}K_1]\!]\Delta$ is defined, so by definition of the interpretation $[\![\Gamma]\!]\Delta'$ is defined and $A_1[\gamma] \in [\![K_1]\!]_{\cdot}\gamma\Delta'$ for $\gamma \in [\![\Gamma]\!]\Delta'$, for any $\vdash_S \Delta' \geq \Delta$.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. We want to show $(\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma] \in [\![\Pi X{\leq}A_1{:}K_1.K_2]\!]_{\cdot}\gamma\Delta$. We have to show two conditions:

- $\Delta \vdash_S (\Pi X{\leq}A_1{:}K_1.K_2)[\gamma] \twoheadrightarrow_{\mathrm{n}} K'$ and $(\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma]$ is a semantic object for Δ and K'. By Lemma 5.5 Case 1 $\Delta \vdash_S K_1[\gamma] \twoheadrightarrow_{\mathrm{n}} K_1'$, and by Lemma 5.6 Case 1 $\Delta \vdash_S A_1[\gamma] \twoheadrightarrow_{\mathrm{n}} A_1' : K_1'$. Hence $\Delta, Y{\leq}A_1[\gamma]{:}K_1[\gamma] \vdash_S \mathrm{ok}$ for Y fresh in Δ.
  By Lemma 5.7 Case 3 $\gamma \in [\![\Gamma]\!]\Delta$ implies $\gamma \in [\![\Gamma]\!]\Delta, Y{\leq}A_1[\gamma]{:}K_1[\gamma]$. By Lemma 5.6 Case 6 $(Y, A_1[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta, Y{\leq}A_1[\gamma]{:}K_1[\gamma]$. Hence

  $$\gamma[X{:=}Y] \in [\![\Gamma, X{\leq}A_1{:}K_1]\!]\Delta, Y{\leq}A_1[\gamma]{:}K_1[\gamma]$$

  so by inductive hypothesis $A_2[\gamma[X{:=}Y]] \in [\![K_2]\!]_{:}\gamma[X{:=}Y]\Delta'$. Hence

  $$\begin{array}{lll} \Delta, Y{\leq}A_1[\gamma]{:}K_1[\gamma] & \vdash_S & K_2[\gamma[X{:=}Y]] \twoheadrightarrow_{\mathrm{n}} K_2' \\ \Delta, Y{\leq}A_1[\gamma]{:}K_1[\gamma] & \vdash_S & A_2[\gamma[X{:=}Y]] \twoheadrightarrow_{\mathrm{n}} A_2' : K_2' \\ \Delta, Y{\leq}A_1[\gamma]{:}K_1[\gamma] & \vdash_S & A_2[\gamma[X{:=}Y]] \leq \mathrm{T}_{K_2'} : K_2' \end{array}$$

  by Lemma 5.6 Case 1 and definition of semantic object. Hence,

  $$\begin{array}{lll} \Delta & \vdash_S & (\Pi X{\leq}A_1{:}K_1.K_2)[\gamma] \twoheadrightarrow_{\mathrm{n}} \Pi Y{\leq}A_1'{:}K_1'.K_2' \\ \Delta & \vdash_S & (\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma] \equiv \Lambda Y{\leq}A_1[\gamma]{:}K_1[\gamma].A_2[\gamma[X{:=}Y]] \\ & \twoheadrightarrow_{\mathrm{n}} & \Lambda Y{\leq}A_1'{:}K_1'.A_2' : \Pi Y{\leq}A_1'{:}K_1'.K_2' \\ \Delta & \vdash_S & (\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma] \leq \Lambda Y{\leq}A_1'{:}K_1'.\mathrm{T}_{K_2'} \equiv \mathrm{T}_{\Pi Y{\leq}A_1'{:}K_1'.K_2'} \\ & : & \Pi Y{\leq}A_1'{:}K_1'.K_2' \end{array}$$

  where the last line follows using Adequacy and Subject Reduction for the well-typedness of the right-hand side. Hence, $(\Pi X{\leq}A_1{:}K_1.K_2)[\gamma]$ is a semantic object for Δ and $\Pi Y{\leq}A_1'{:}K_1'.K_2'$.
- $(\Pi X{\leq}A_1{:}K_1.K_2)[\gamma]\, B \in [\![K_2]\!]_{:}\gamma[X{:=}B]\Delta'$, with $\vdash_S \Delta' \geq \Delta$ and $(B, A_1[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta'$. First, by Lemma 5.7 Case 3 $\gamma \in [\![\Gamma]\!]\Delta$ implies $\gamma \in [\![\Gamma]\!]\Delta'$, and $(B, A_1[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta'$ implies $\gamma[X{:=}B] \in [\![\Gamma, X{\leq}A_1{:}K_1]\!]\Delta'$ by definition of the interpretation. Hence by inductive hypothesis $A_2[\gamma[X{:=}B]] \in [\![K_2]\!]_{:}\gamma[X{:=}B]\Delta'$, and so by Lemma 5.6 Case 1 $\Delta' \vdash_S A_2[\gamma[X{:=}B]] \twoheadrightarrow_{\mathrm{w}} C : K_2''$, where $\Delta' \vdash_S K_2[\gamma[X{:=}B]] \twoheadrightarrow_{\mathrm{n}} K_2''$. Then $\Delta \vdash_S (\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma] : \Pi Y{\leq}A_1'{:}K_1'.K_2'$ implies $\Delta' \vdash_S (\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma] : \Pi Y{\leq}A_1'{:}K_1'.K_2'$ by Thinning, and $\Delta' \vdash_S B \leq A_1[\gamma] : K_1'$ by Lemma 5.6 Case 2. Hence

  $$\begin{array}{lll} \Delta' & \vdash_S & (\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma](B) \\ & \equiv & (\Lambda Y{\leq}A_1[\gamma]{:}K_1[\gamma].A_2[\gamma[X{:=}Y]])(B) \twoheadrightarrow_{\mathrm{w}} C : K_2'' \end{array}$$

  by ST-Beta, because $A_2[\gamma[X{:=}Y]][Y{\leftarrow}B] \equiv A_2[\gamma[X{:=}B]]$ where Y can be chosen to be fresh in Δ'. Hence, by Lemma 5.6 Case 7

  $$(\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma](B) \in [\![K_2]\!]_{:}\gamma[X{:=}B]\Delta'$$

Hence, $(\Lambda X{\leq}A_1{:}K_1.A_2)[\gamma](B) \in [\![\Pi X{\leq}A_1{:}K_1.K_2]\!]_{:}\gamma\Delta$.

T-TApp By inductive hypothesis $[\![\Gamma]\!]\Delta$ is defined.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. Then $A[\gamma] \in [\![\Pi X{\leq}B{:}K_1.K_2]\!]_{:}\gamma\Delta$ and $(C[\gamma], B[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta$. Clearly $\vdash_S \Delta \geq \Delta$, since $\Delta \vdash_S \mathrm{ok}$ by Lemma 5.5 Case 2, so

$$(A[\gamma])(C[\gamma]) \equiv (A\,C)[\gamma] \in [\![K_2]\!]_{:}\gamma[X{:=}C[\gamma]] = [\![K_2[X{\leftarrow}C]]\!]_{:}\gamma\Delta$$

where the last equality follows by Lemma 5.8 Case 2.

T-Eq-TApp By inductive hypothesis $[\![\Gamma]\!]\Delta$ is defined.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. By inductive hypothesis $A[\gamma], B[\gamma] \in [\![\Pi X{\leq}E{:}K_1.K_2]\!]_{:}\gamma\Delta$, $\Delta \vdash_S A[\gamma], B[\gamma] \twoheadrightarrow_{\mathrm{n}} A' : \Pi X{\leq}E'{:}K_1'.K_2'$ with $\Delta \vdash_S (\Pi X{\leq}E{:}K_1.K_2)[\gamma] \twoheadrightarrow_{\mathrm{n}} \Pi X{\leq}E'{:}K_1'.K_2'$, and also $C[\gamma], D[\gamma] \in [\![K_1]\!]_{:}\gamma\Delta$, $\Delta \vdash_S C[\gamma], D[\gamma] \twoheadrightarrow_{\mathrm{n}} C' : K_1'$, and finally $(C[\gamma], E[\gamma]) \in [\![K_1]\!]_{\leq}\gamma\Delta$. Hence,

$$\begin{array}{rcl}(A[\gamma])(C[\gamma]) \equiv (AC)[\gamma] & \in & [\![K_2]\!]_{:}\gamma[X{:=}C[\gamma]]\Delta = [\![K_2[X{\leftarrow}C]]\!]_{:}\gamma\Delta \\ (B[\gamma])(D[\gamma]) \equiv (BD)[\gamma] & \in & [\![K_2]\!]_{:}\gamma[X{:=}D[\gamma]]\Delta = [\![K_2[X{\leftarrow}D]]\!]_{:}\gamma\Delta\end{array}$$

Using Adequacy, Subject Reduction and Determinacy we conclude that

$$\Delta \vdash_S (AC)[\gamma], (BD)[\gamma] \twoheadrightarrow_{\mathrm{n}} F : K_2'$$

where $\Delta \vdash_S K_2[X{\leftarrow}C] \twoheadrightarrow_{\mathrm{n}} K_2'$. Finally, $\Delta \vdash_S \gamma[X{:=}C[\gamma]], \gamma[X{:=}D[\gamma]] \twoheadrightarrow_{\mathrm{n}} \gamma'$, so by Lemma 5.5 Case 4:

$$(BD)[\gamma] \in [\![K_2]\!]_{:}\gamma[X{:=}C[\gamma]]\Delta = [\![K_2[X{\leftarrow}C]]\!]_{:}\gamma\Delta$$

S-Top By inductive hypothesis $[\![\Gamma]\!]\Delta$ is defined.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. Then $A[\gamma] \in [\![K]\!]_{:}\gamma\Delta$, so by Lemma 5.6 Case 8 $(A[\gamma], \mathrm{T}_{K[\gamma]}) \in [\![K]\!]_{\leq}\gamma\Delta$, and $\mathrm{T}_{K[\gamma]} \equiv \mathrm{T}_K[\gamma]$.

S-Trans By inductive hypothesis $[\![\Gamma]\!]\Delta$ is defined.

Suppose $\gamma \in [\![\Gamma]\!]\Delta$. By inductive hypothesis $(A[\gamma], B[\gamma]) \in [\![K]\!]_{\leq}\gamma\Delta$ and $(B[\gamma], C[\gamma]) \in [\![K]\!]_{\leq}\gamma\Delta$. Hence by Lemma 5.6 Case 5 $(A[\gamma], C[\gamma]) \in [\![K]\!]_{\leq}\gamma\Delta$. □

Lemma 5.11 If $\Gamma \vdash \mathrm{ok}$ then $\mathrm{id}_\Gamma \in [\![\Gamma]\!]\Gamma$, where id_Γ is the identity substitution on Γ.

Proof: By induction on Γ, using several simple generation lemmas for contexts. □

Corollary 5.12 (*Soundness*)

1. If $\Gamma \vdash A : K$ then there are K', B and C such that $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$ and $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{w}} B \ {}_{\mathrm{w}}\!\!\twoheadrightarrow_{\mathrm{n}} C : K'$.
2. If $\Gamma \vdash A \leq B : K$ then there is a K' such that $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$ and $\Gamma \vdash_S A \leq B : K'$.

5.4 Consequences of Soundness

We can use Soundness, Corollary 5.12, and Completeness, Proposition 4.6, to transfer the metatheoretic results from the typed operational semantics to the original presentation.

Lemma 5.13 (*Admissibility of Structural Rules*) The rules in Section 2.3 are admissible for the system $\Gamma \vdash^{-} J$.

Proof: Suppose we have a derivation of $\Gamma \vdash J$, for example $\Gamma \vdash A : K$, which is then a derivation of $\Gamma \vdash^{-} J$ with uses of the structural rules in Section 2.3. By Soundness we know that there are B and K' such that $\Gamma \vdash_S A \twoheadrightarrow_{\mathrm{n}} B : K'$ and $\Gamma \vdash_S K \twoheadrightarrow_{\mathrm{n}} K'$. By Completeness $\Gamma \vdash^{-} A : K'$ and $\Gamma \vdash^{-} K = K'$, so by T-Conv $\Gamma \vdash^{-} A : K$. □

LEMMA 5.14 (*Strong Normalization*) If $\Gamma \vdash A : K$ then A is strongly normalizing.

PROOF: By Soundness and Strong Normalization (Lemma 4.15). □

LEMMA 5.15 (*Subject Reduction for* $\rightarrow_{\beta_2}$)

- If $\Gamma \vdash \mathrm{ok}$ and $\Gamma \rightarrow_{\beta_2} \Gamma'$ then $\Gamma' \vdash \mathrm{ok}$.
- If $\Gamma \vdash K$ and $K \rightarrow_{\beta_2} K'$ then $\Gamma \vdash K$ and $\Gamma \vdash K =_\beta K'$.
- If $\Gamma \vdash A : K$ and $A \rightarrow_{\beta_2} B$ then $\Gamma \vdash A : K$ and $\Gamma \vdash A =_\beta B : K$.
- If $\Gamma \vdash A \leq B : K$ and $A \rightarrow_{\beta_2} C$ then $\Gamma \vdash C \leq B : K$, or if $B \rightarrow_{\beta_2} C$ then $\Gamma \vdash A \leq C : K$.

PROOF: By Soundness, Subject Reduction (Corollary 4.13), and Completeness. □

PROPOSITION 5.16 (*Generation for Subtyping*)

1. If $\Gamma \vdash (A_1 \rightarrow A_2) \leq (B_1 \rightarrow B_2) : \star$ then $\Gamma \vdash B_1 \leq A_1 : \star$ and $\Gamma \vdash A_2 \leq B_2 : \star$
2. If $\Gamma \vdash (\forall X \leq A_1 : K_A . A_2) \leq (\forall X \leq B_1 : K_B . B_2) : \star$ then $\Gamma \vdash K_A =_\beta K_B$, $\Gamma \vdash A_1 =_\beta B_1 : K_A$, and $\Gamma, X \leq A_1 : K_A \vdash A_2 \leq B_2 : \star$.

PROOF:

1. By Soundness $\Gamma \vdash_S A_1 \rightarrow A_2 \leq B_1 \rightarrow B_2 : \star$. Since the semantic presentation is deterministic the latter must have been obtained by SS-INC and SWS-ARROW from $\Gamma \vdash_S B_1 \leq A_1 : \star$ and $\Gamma \vdash_S A_2 \leq B_2 : \star$. Then, by Completeness, $\Gamma \vdash B_1 \leq A_1 : \star$ and $\Gamma \vdash A_2 \leq B_2 : \star$.
2. By Soundness $\Gamma \vdash_S \forall X \leq A_1 : K_A . A_2 \leq \forall X \leq B_1 : K_B . B_2 : \star$. Since the semantic presentation is deterministic the latter must have been obtained by SS-INC and SWS-ALL from $\Gamma, X \leq A_1 : K_A \vdash_S A_2 \leq B_2 : \star$, $\Gamma \vdash_S A_1, B_1 \twoheadrightarrow_{\mathrm{n}} C : K''$, and $\Gamma \vdash_S K_A, K_B \twoheadrightarrow_{\mathrm{n}} K''$. By Completeness $\Gamma, X \leq A_1 : K_A \vdash A_2 \leq B_2 : \star$, and also $\Gamma \vdash A_1 =_\beta C : K''$, $\Gamma \vdash B_1 =_\beta C : K''$, $\Gamma \vdash K_A =_\beta K''$, and $\Gamma \vdash K_B =_\beta K''$. Hence by T-EQ-SYM, T-EQ-TRANS, K-EQ-SYM, K-EQ-TRANS, it follows that $\Gamma \vdash K_A =_\beta K_B$, and also that $\Gamma \vdash A_1 =_\beta B_1 : K''$, and $\Gamma \vdash K'' =_\beta K_A$. Finally, by T-EQ-CONV, $\Gamma \vdash A_1 =_\beta B_1 : K_A$. □

PROPOSITION 5.17 (*Generation for Typing*)

1. If $\Gamma \vdash \lambda x : A_1 . M : A$ then there exists an A_2 such that $\Gamma, x : A_1 \vdash M : A_2$ and $\Gamma \vdash A_1 \rightarrow A_2 \leq A : \star$.
2. If $\Gamma \vdash \lambda X \leq A_1 : K . M : A$ then there exists an A_2 such that $\Gamma, X \leq A_1 : K \vdash M : A_2$ and $\Gamma \vdash \forall X \leq A_1 : K . A_2 \leq A : \star$.

PROOF: Each case follows by induction on the derivation of the antecedent. □

LEMMA 5.18 (*Agreement*)

1. If $\Gamma_1, x : A, \Gamma_2 \vdash \mathrm{ok}$ then $\Gamma_1 \vdash A : \star$.
2. If $\Gamma_1, X \leq A : K, \Gamma_2 \vdash \mathrm{ok}$ then $\Gamma_1 \vdash A : K$.
3. If $\Gamma \vdash M : A$ then $\Gamma \vdash A : \star$.

PROOF: We use Lemma 4.23, Soundness and Completeness. □

6 Subject Reduction

PROPOSITION 6.1 ($\rightarrow_{\beta_1}$ *Subject Reduction for Terms*)
If $\Gamma \vdash M : A$ and $M \rightarrow_{\beta_1} M'$ then $\Gamma \vdash M' : A$.

PROOF: By induction on the derivation of $\Gamma \vdash M : A$.

T-VAR Vacuously true.

T-ABS By the induction hypothesis and T-ABS.

T-APP Let $M \equiv N\,a$. Then we are given that $\Gamma \vdash N : A_1 \rightarrow A$ and $\Gamma \vdash a : A_1$. There are 3 cases to consider. If $N \rightarrow_{\beta_1} N'$ or $a \rightarrow_{\beta_1} a'$ then the result follows by the induction hypothesis and T-APP. The interesting case is when $N \equiv \lambda x{:}B_1.N'$ and $M \rightarrow_{\beta_1} N'[x \leftarrow a]$. By Generation for Typing (Proposition 5.17), $\Gamma, x{:}B_1 \vdash N' : B_2$ and $\Gamma \vdash B_1 \rightarrow B_2 \leq A_1 \rightarrow A$, for some B_2. By Generation for Subtyping (Proposition 5.16) $\Gamma \vdash A_1 \leq B_1$ and $\Gamma \vdash B_2 \leq A$. By T-SUB, $\Gamma \vdash a : B_1$, and, by Substitution (Lemma 4.26), $\Gamma \vdash N'[x \leftarrow a] : B_2$. Finally, by T-SUB, $\Gamma \vdash N'[x \leftarrow a] : A$.

T-TABS By the induction hypothesis and T-TABS.

T-TAPP Let $M \equiv N\,B$. We are given that $\Gamma \vdash N : \forall X \leq A_1{:}K_A.A_2$, $\Gamma \vdash B \leq A_1 : K_A$, and $A \equiv A_2[X \leftarrow B]$. There are two cases to consider. If $N \rightarrow_{\beta_1} N'$ then the result follows by the induction hypothesis and T-TAPP. Otherwise, $N \equiv \lambda X \leq B_1{:}K_B.N'$ and $M' \equiv N'[X \leftarrow B]$. By Generation for Typing (Proposition 5.17), $\Gamma, X \leq B_1{:}K_B \vdash N' : B_2$, and $\Gamma \vdash \forall X \leq B_1{:}K_B.B_2 \leq \forall X \leq A_1{:}K_A.A_2 : \star$, for some B_2. By Generation for Subtyping (Proposition 5.16), $\Gamma, X \leq A_1{:}K_A \vdash B_2 \leq A_2 : \star$, $\Gamma \vdash A_1 =_\beta B_1 : K_A$, and $\Gamma \vdash K_A =_\beta K_B$. By S-CONV, $\Gamma \vdash A_1 \leq B_1 : K_A$, and, by S-TRANS, $\Gamma \vdash B \leq B_1 : K_A$. By Substitution (Lemma 4.26), $\Gamma \vdash N'[X \leftarrow B] : B_2[X \leftarrow B]$. By SUBST, $\Gamma \vdash B_2[X \leftarrow B] \leq A_2[X \leftarrow B] : \star$. Finally, by T-SUB $\Gamma \vdash N'[X \leftarrow B] : A_2[X \leftarrow B] : \star$.

T-SUB By the induction hypothesis and T-SUB. □

LEMMA 6.2 If $\Gamma \vdash M : A$ and $\Gamma \rightarrow_{\beta_2} \Gamma'$ then $\Gamma' \vdash M : A$.

PROOF: By induction on derivations using Lemma 5.15. □

LEMMA 6.3 If $C \rightarrow_{\beta_2} C'$ then $B[X \leftarrow C] \twoheadrightarrow_{\beta_2} B[X \leftarrow C']$.

PROPOSITION 6.4 ($\rightarrow_{\beta_2}$ *Subject Reduction for Terms*)
If $\Gamma \vdash M : A$ and $M \rightarrow_{\beta_2} M'$ then $\Gamma \vdash M' : A$.

PROOF: By induction on derivations.

T-VAR Vacuously true.

T-ABS There are two cases to consider.

1. $A \rightarrow_{\beta_2} A'$. By Lemma 6.2, $\Gamma, x{:}A' \vdash M : B$, by T-ABS, $\Gamma \vdash \lambda x{:}A'.M : A' \rightarrow B$. By Lemma 5.18 Case 1 and Lemma 4.23 we conclude $\Gamma \vdash A : \star$ from $\Gamma, x{:}A \vdash M : B$. By Lemma 5.15, $\Gamma \vdash A =_\beta A' : \star$. By Lemma 5.18 Case 3, $\Gamma, x{:}A' \vdash B : \star$, by Strengthening (Lemma 4.24), $\Gamma \vdash B : \star$, by T-EQ-REFL, $\Gamma \vdash B =_\beta B : \star$, by T-EQ-ARROW and T-EQ-SYM, $\Gamma \vdash A' \rightarrow B =_\beta A \rightarrow B : \star$. Then, by S-CONV, $\Gamma \vdash A' \rightarrow B \leq A \rightarrow B : \star$, and by T-SUB $\Gamma \vdash \lambda x{:}A'.M : A \rightarrow B$

2. $M \rightarrow_{\beta_2} M'$. By the induction hypothesis and T-Abs.

T-App There are two cases to consider, either $M \rightarrow_{\beta_2} M'$ or $N \rightarrow_{\beta_2} N'$. Both cases follow by the induction hypothesis and T-App.

T-TAbs There are three cases to consider.

1. If $M \rightarrow_{\beta_2} M'$, the result follows by the induction hypothesis and T-TAbs.
2. If $A \rightarrow_{\beta_2} A'$, it is similar to T-Abs case 1.
3. If $K \rightarrow_{\beta_2} K'$, by Lemma 6.2, $\Gamma,\ X{\leq}A{:}K' \vdash M : B$, by T-TAbs, $\Gamma \vdash \lambda X{\leq}A{:}K'.M : \forall X{\leq}A{:}K'.B$. From $\Gamma,\ X{\leq}A{:}K \vdash M : B$, by Lemma 4.23 and Lemma 5.18 Case 2, $\Gamma \vdash A : K$, and, by the rule Kind-Agreement, $\Gamma \vdash K$. By Lemma 5.15, $\Gamma \vdash K =_\beta K'$, by T-EQ-Refl, $\Gamma \vdash A =_\beta A : K$. With a similar argument to that used in the T-Abs case we prove that $\Gamma \vdash B =_\beta B : \star$. Now, by T-EQ-Sym and T-EQ-All, $\Gamma \vdash \forall X{\leq}A{:}K'.B =_\beta \forall X{\leq}A{:}K.B : \star$, by S-Conv, $\Gamma \vdash \forall X{\leq}A{:}K'.B \leq \forall X{\leq}A{:}K.B : \star$. Finally, by T-Sub, $\Gamma \vdash \lambda X{\leq}A{:}K'.M : \forall X{\leq}A{:}K.B$.

T-TApp There are two cases to consider.

1. If $M \rightarrow_{\beta_2} M'$ then the result follows by the induction hypothesis and T-TApp.
2. If $C \rightarrow_{\beta_2} C'$, by Lemma 4.13, $\Gamma \vdash C' \leq A : K$, by T-TApp, $\Gamma \vdash M\,C' : B[X{\leftarrow}C']$, by Lemma 5.18 Case 3, $\Gamma \vdash B[X{\leftarrow}C] : \star$, by Lemma 6.3 and Lemma 5.15, $\Gamma \vdash B[X{\leftarrow}C] =_\beta B[X{\leftarrow}C'] : \star$, by T-EQ-Sym and T-Sub, $\Gamma \vdash M\,C' : B[X{\leftarrow}C]$.

T-Sub By the induction hypothesis and T-Sub. □

Proposition 6.5 ($\twoheadrightarrow_\beta$ *Subject Reduction for Terms*)
If $\Gamma \vdash M : A$ and $M \twoheadrightarrow_\beta M'$ then $\Gamma \vdash M' : A$.

Proof: The proof is by induction on the definition of $\twoheadrightarrow_\beta$. The reflexive case is immediate, the cases for $\rightarrow_{\beta_1}$ and $\rightarrow_{\beta_2}$ follow by Propositions 6.1 and 6.4 respectively, and the transitivity case follows by the induction hypothesis. □

7 An Algorithmic Presentation

From the rules for subtyping in the typed operational semantics we extract an algorithm that computes the subtyping relation on weak head normal forms, ignoring kind information and well-formation of contexts. The reductions to weak head normal form are then untyped calculations defined as follows:

$$\begin{array}{rcll} A & \twoheadrightarrow_{\mathrm{w}} & A & \text{if } A \text{ is weak head normal.} \\ A\,B & \twoheadrightarrow_{\mathrm{w}} & C\,D & \text{if } A \twoheadrightarrow_{\mathrm{w}} C,\ B \twoheadrightarrow_{\mathrm{n}} D, \text{ and } C \neq \Lambda X{\leq}E{:}K.F \\ A\,B & \twoheadrightarrow_{\mathrm{w}} & E & \text{if } A \twoheadrightarrow_{\mathrm{w}} \Lambda X{\leq}C{:}K.D \text{ and } D[X{\leftarrow}B] \twoheadrightarrow_{\mathrm{w}} E \end{array}$$

where $\twoheadrightarrow_{\mathrm{n}}$ is defined simultaneously by recursively finding the normal form of each subterm in a weak head normal form.

The algorithm to compute the subtyping relation is defined by the following rules.

7.1 Algorithmic Subtyping

$$\frac{A \twoheadrightarrow_{\mathrm{w}} C \qquad B \twoheadrightarrow_{\mathrm{w}} D \qquad \Gamma \vdash_A C \leq_W D}{\Gamma \vdash_A A \leq B} \tag{AS-Inc}$$

This rule reduces the arguments to weak head normal and then invokes the weak-head subtyping algorithm defined as follows.

7.2 Weak-Head Subtyping

$$\Gamma \vdash_A A \leq_W \mathrm{T}_\star \qquad A \text{ does not have a head variable} \tag{AWS-Top}$$

$$\frac{\begin{array}{ll}\Gamma(X) \twoheadrightarrow_{\mathrm{n}} B & \Gamma \vdash_A E \leq_W C \\ B(A_1, \ldots, A_m) \twoheadrightarrow_{\mathrm{w}} E & C \neq X(A_1, \ldots A_n)\end{array}}{\Gamma \vdash_A X(A_1, \ldots, A_m) \leq_W C : K} \tag{AWS-TApp}$$

$$\Gamma \vdash_A X(A_1, \ldots, A_m) \leq_W X(A_1, \ldots, A_m) \tag{AWS-Refl}$$

$$\frac{\Gamma \vdash_A B_1 \leq A_1 \qquad \Gamma \vdash_A A_2 \leq B_2}{\Gamma \vdash_A A_1 \to A_2 \leq_W B_1 \to B_2} \tag{AWS-Arrow}$$

$$\frac{\Gamma, X \leq A_1 : K \vdash_A A_2 \leq B_2 \qquad \mathrm{nf}(A_1) = \mathrm{nf}(B_1) \qquad \mathrm{nf}(K) = \mathrm{nf}(K')}{\Gamma \vdash_A \forall X \leq A_1 : K . A_2 \leq_W \forall X \leq B_1 : K' . B_2} \tag{AWS-All}$$

$$\frac{\Gamma, X \leq A_1 : K_1 \vdash_A A_2 \leq B_2 \qquad \mathrm{nf}(A_1) = \mathrm{nf}(B_1)}{\Gamma \vdash_A \Lambda X \leq A_1 : K_1 . A_2 \leq_W \Lambda X \leq B_1 : K_1' . B_2} \tag{AWS-TAbs}$$

Our aim is to prove that this algorithm is sound with respect to the original system on well-formed types: if $\Gamma \vdash_A A \leq B$ and $\Gamma \vdash A, B : K$ then $\Gamma \vdash A \leq B : K$. The problem we encounter is that the original system uses subtyping to check $\Gamma \vdash A, B : K$. Therefore we need algorithmic versions of the judgements involved in proving well-kindedness.

The algorithmic rules for the other judgements are modifications of the $\mathcal{F}^{\omega}_{\leq}$ rules and not of the typed operational semantics. The rules for Context Formation are identical, and in Kind and Type Formation the assumptions of the form $\Gamma \vdash \mathrm{ok}$ are dropped. The rules AK-Π, AT-All and AT-TAbs need the side condition $X \notin \mathrm{dom}(\Gamma)$ and the rule AT-TApp uses an arbitrary normalization procedure.

7.3 Algorithmic Context Formation

$$\emptyset \vdash_A \mathrm{ok} \tag{AC-Empty}$$

$$\frac{\Gamma \vdash_A A : \star \qquad x \notin \mathrm{dom}(\Gamma)}{\Gamma, x : A \vdash_A \mathrm{ok}} \tag{AC-Var}$$

$$\frac{\Gamma \vdash_A A : K \qquad X \notin \mathrm{dom}(\Gamma)}{\Gamma, X \leq A : K \vdash_A \mathrm{ok}} \tag{AC-TVar}$$

7.4 Algorithmic Kind Formation

$$\Gamma \vdash_A \star \tag{AK-$\star$}$$

$$\frac{\Gamma, X \leq A : K_1 \vdash_A K_2 \qquad \Gamma \vdash_A A : K_1 \qquad X \notin \mathrm{dom}(\Gamma)}{\Gamma \vdash_A \Pi X \leq A : K_1 . K_2} \tag{AK-Π}$$

7.5 Algorithmic Type Formation

$$\Gamma \vdash_A \mathrm{T}_\star : \star \tag{AT-Top}$$

$$\Gamma_1, X{\leq}A{:}K, \Gamma_2 \vdash_A X : K \qquad \text{(AT-TVar)}$$

$$\frac{\Gamma \vdash_A A_1 : \star \qquad \Gamma \vdash_A A_2 : \star}{\Gamma \vdash_A A_1 {\to} A_2 : \star} \qquad \text{(AT-Arrow)}$$

$$\frac{\Gamma, X{\leq}A_1{:}K \vdash_A A_2 : \star \qquad \Gamma \vdash_A A_1 : K_1 \qquad X \notin \mathrm{dom}(\Gamma)}{\Gamma \vdash_A \forall X{\leq}A_1{:}K.A_2 : \star} \qquad \text{(AT-All)}$$

$$\frac{\Gamma, X{\leq}A_1{:}K_1 \vdash_A A_2 : K_2 \qquad \Gamma \vdash_A A : K_1 \qquad X \notin \mathrm{dom}(\Gamma)}{\Gamma \vdash_A \Lambda X{\leq}A_1{:}K_1.A_2 : \Pi X{\leq}A_1{:}K_1.K_2} \qquad \text{(AT-TAbs)}$$

$$\frac{\Gamma \vdash_A A : \Pi X{\leq}B{:}K_1.K_2 \qquad \Gamma \vdash_A C \leq B \qquad \Gamma \vdash_A C : K_1' \qquad \mathrm{nf}(K) = \mathrm{nf}(K')}{\Gamma \vdash_A A\,C : K_2[X{\leftarrow}C]} \qquad \text{(AT-TApp)}$$

Proposition 7.1 (*Correctness of the Algorithm*)

1. If $\Gamma \vdash_A \mathrm{ok}$ then $\Gamma \vdash \mathrm{ok}$.
2. Given $\Gamma \vdash \mathrm{ok}$. If $\Gamma \vdash_A K$ then $\Gamma \vdash K$.
3. Given $\Gamma \vdash \mathrm{ok}$. If $\Gamma \vdash_A A : K$ then $\Gamma \vdash A : K$.
4. Given $\Gamma \vdash A, B : K$. If $\Gamma \vdash_A A \leq_W B$ then $\Gamma \vdash A \leq B : K$.
5. Given $\Gamma \vdash A, B : K$. If $\Gamma \vdash_A A \leq B$ then $\Gamma \vdash A \leq B : K$.

Proof: By induction on derivations, using Soundness (Corollary 5.12), Completeness (Proposition 4.6), and Subject Reduction (Corollary 4.13). □

Proposition 7.2 (*Completeness of the Algorithm*)

1. If $\Gamma \vdash_S \mathrm{ok}$ then $\Gamma \vdash_A \mathrm{ok}$.
2. If $\Gamma \vdash_S K$ then $\Gamma \vdash_A K$.
3. If $\Gamma \vdash_S A : K$ then $\Gamma \vdash_A A : K$.
4. If $\Gamma \vdash_S A \leq_W B : K$ then $\Gamma \vdash_A A \leq B$.
5. If $\Gamma \vdash_S A \leq B : K$ then $\Gamma \vdash_A A \leq B$.

Proof: By induction on derivations. The proof is straightforward because all the information in each $\vdash_A$ rules is included in or follows easily from the corresponding $\vdash_S$ rules. □

The last two properties together with the soundness of the semantics (Corollary 5.12) prove that the algorithm is sound and complete with respect to $\mathcal{F}^{\omega}_{\leq}$.

Proposition 7.3 (*Equivalence of the Algorithm and* $\mathcal{F}^{\omega}_{\leq}$)

1. $\Gamma \vdash_A \mathrm{ok}$ iff $\Gamma \vdash \mathrm{ok}$.
2. $\Gamma \vdash \mathrm{ok}$ and $\Gamma \vdash_A K$ iff $\Gamma \vdash K$.
3. $\Gamma \vdash \mathrm{ok}$, $\Gamma \vdash_A A : K'$, and $\Gamma \vdash_A K \twoheadrightarrow_{\mathrm{n}} K'$ iff $\Gamma \vdash A : K$.
4. $\Gamma \vdash A, B : K$ and $\Gamma \vdash_A A \leq B$ iff $\Gamma \vdash A \leq B : K$.

PROOF: By induction on derivations, using Soundness (Corollary 5.12), Completeness (Proposition 4.6), and Subject Reduction (Corollary 4.13). □

By the equivalence, we can use the following sequence to check whether $\Gamma \vdash A \leq B : K$:

1. check that Γ is a good context, $\Gamma \vdash_A \mathrm{ok}$,
2. infer kinds K' and K'' such that $\Gamma \vdash_A A : K'$ and $\Gamma \vdash_A B : K''$,
3. check that the given kind is well formed, $\Gamma \vdash_A K$,
4. check that K', K'' and the normal form of K (which exists by Strong Normalization (Lemma 4.15)) are syntactically equal,
5. check that $\Gamma \vdash_A A \leq B$.

If any of the steps fails then the statement $\Gamma \vdash A \leq B : K$ is not derivable in $\mathcal{F}^{\omega}_{\leq}$, and otherwise it is.

8 Related and Future Work

Bruce [5] uses bounded operator abstraction, but does not develop the metatheory. Compagnoni [11] mentions the open problem of studying the metatheory for bounded operator abstraction.

Most type systems with subtyping do not have the circularity between type formation and subtyping mentioned in the introduction: for example, $F^{\omega}_{<:}$ [7], $F^{\omega}_{\wedge}$ [12], and the systems in Abadi and Cardelli's book on objects [2] all separate the two judgements. One system that does have the circularity is $\lambda P_{\leq}$, a system for subtyping with dependent types studied by Aspinall and Compagnoni [4]. There, the authors avoid the interdependency by finding a particular order in which to prove results.

Some of the difficulties encountered here have already been studied in dependent type theory. Streicher [23] gives a partial interpretation function to define the categorical semantics of the calculus of constructions, a technique which is now widely used. Typed operational semantics has been used to develop the metatheory of *UTT*, a sophisticated type theory with inductive types, impredicative propositions and type universes [16, 17]. Coquand [13] interprets judgemental equality as a logical relation to show properties of Martin-Löf type theory with $\beta\eta$-equality, similar to our interpretation of the subtyping relation.

There are several directions for future work. The proof here should easily extend to a system with $\beta\eta$-equality, the equality for which typed operational semantics was originally developed. We also believe that the model construction can be extended to cope with Γ-reduction, replacing variables X by their bounds A if $X \leq A : K$ is in Γ, which cannot be done directly in the semantics because of an interdependency of transitivity elimination and context replacement. Furthermore, it seems that the model can deal with a limited form of contravariance for quantification over the kind $\star$ but not over arbitrary kinds. Finally, we have not included recursive types or objects, but Abadi and Cardelli [2] have demonstrated that these do not present difficulties at the level of types, and our proof should extend without any problems.

9 Conclusions

In this paper we have studied $\mathcal{F}^{\omega}_{\leq}$, the first treatment of the metatheory for a system of higher-order subtyping with bounded operator abstraction. We have used techniques for constructing models for dependent type theory to solve problems associated with the weak dependency introduced by bounds in kinds, and we have modeled the subtyping relation directly rather than using a syntactic encoding. We have also used the new tool of typed operational semantics to give simpler proofs for meta-theoretic properties such as substitution, kind correctness, and subject reduction and Church–Rosser for type reduction. Finally, we have shown the equivalence with the algorithmic presentation of the system. Because the techniques introduced are adapted from other contexts and do not involve encodings of syntax, we believe that they are generally applicable.

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