

The Combination of Dynamic and Static Typing from a Categorical Perspective

Harley Eades III^{1,2}

*Computer and Information Sciences
Augusta University
Augusta, USA*

Michael Townsend³

*Computer and Information Sciences
Augusta University
Augusta, USA*

Abstract

In this paper we introduce a new categorical model based on retracts that combines static and dynamic typing. This model is initially based on the seminal work of Scott who showed that the untyped λ -calculus can be considered as typed using retracts. We then show that our model gives rise to a new and simple type system which combines static and dynamic typing. Finally, we extend this type system with bounded quantification and lists, and then develop a gradually typed surface language that uses our new type system as a core casting calculus. This paper can be seen as the first of a new project to investigate the categorical semantics of gradual type systems.

Keywords: static typing, dynamic typing, gradual typing, categorical semantics, retract, typed lambda-calculus, untyped lambda-calculus, gradual typing, static typing, dynamic typing, categorical model, functional programming

1 Introduction

Scott [7] showed how to model the untyped λ -calculus within a cartesian closed category, \mathcal{C} , with a distinguished object we will call $?$ – read as the type of untyped terms – such that the object $^4 ? \rightarrow ?$ is a retract of $?$. That is, there are morphisms $\text{squash} : (? \rightarrow ?) \longrightarrow ?$ and $\text{split} : ? \longrightarrow (? \rightarrow ?)$ where $\text{squash} \circ \text{split} = \text{id} : (? \rightarrow ?) \longrightarrow (? \rightarrow ?)$ ⁵. For example, taking these morphisms as terms in the typed

¹ Thanks: TODO

² Email: heades@augusta.edu

³ Email: mitownsend@augusta.edu

⁴ We will use the terms “object” and “type” interchangeably.

⁵ We denote composition of morphisms by $f;g : A \longrightarrow C$ given morphisms $f : A \longrightarrow B$ and $g : B \longrightarrow C$.

λ -calculus we can define the prototypical looping term $(\lambda x.xx)(\lambda x.xx)$ by $(\lambda x : ?.(split\ x)\ x)(squash\ (\lambda x : ?.(split\ x)\ x))$.

In the same volume as Scott, Lambek [5] showed that cartesian closed categories also model the typed λ -calculus. Suppose we want to model the typed λ -calculus with pairs and natural numbers. That is, given two types A_1 and A_2 there is a type $A_1 \times A_2$, and there is a type \mathbf{Nat} . Furthermore, we have first and second projections, and zero and successor functions. This situation can easily be modeled by a cartesian closed category \mathcal{C} – see Section ?? for the details. Now combine both of Scott and Lambek’s work by adding to \mathcal{C} the type of untyped terms $?$, **squash**, and **split**. At this point \mathcal{C} is a model of both the typed and the untyped λ -calculus. However, the two theories are really just sitting side by side in \mathcal{C} and cannot really interact much.

Suppose A is an atomic type. Then we add to \mathcal{C} the morphisms $\mathbf{box} : A \longrightarrow ?$ and $\mathbf{unbox} : ? \longrightarrow A$ such that $\mathbf{box}; \mathbf{unbox} = \text{id} : A \longrightarrow A$ making A a retract of $?$. This is the bridge allowing the typed world to interact with the untyped one. We can think of **box** as injecting typed data into the untyped world, and **unbox** as taking it back. Notice that the only time we can actually get the typed data back out is if it were injected into the untyped world initially. In the model this is enforced through composition, but in the language this will be enforced at runtime, and hence, requires the language to contain dynamic typing. Thus, what we have just built up is a categorical model that offers a new perspective of how to combine static and dynamic typing.

Siek and Taha [8] define gradual typing to be the combination of both static and dynamic typing that allows for the programmer to program in dynamic style without the need for the them to explicitly insert casts into their programs. Siek and Taha’s initial paper laid out the first gradually typed λ -calculus, but Siek et al. [9] layout a refined criteria for what metatheoretic properties a gradual type system should have called the gradual guarantee. In this paper we show that our categorical model leads to a new core casting calculus for gradual type systems.

Siek and Taha’s gradually typed λ -calculus is defined as the simply typed λ -calculus with the type of untyped terms $?$ and the following new application rule:

$$\frac{\Gamma \vdash_S t_1 : C \quad \Gamma \vdash_S t_2 : A_2 \quad A_2 \sim A_1 \quad \text{fun}(C) = A_1 \rightarrow B_1}{\Gamma \vdash_S t_1 t_2 : B_1} \rightarrow_e$$

The premise $A_2 \sim A_1$ is read, the type A_2 is consistent with the type A_1 , and is defined in Figure ??. If we squint we can see **split**, **squash**, **box**, and **unbox** hiding in the definition of the previous rules, but they have been suppressed. We will show that when one uses either of the two typing rules then one is really implicitly using a casting morphism built from **split**, **squash**, **box**, and **unbox**. In fact, the consistency relation $A \sim B$ can be interpreted as such a morphism. Then the typing above can be read semantically as a saying if a casting morphism exists, then the type really can be converted into the necessary type. The premise $\text{fun}(C) = A_1 \rightarrow B_1$ requires that C either be $A_1 \rightarrow B_1$ or $C = ?$ and $\text{fun}(C) = ? \rightarrow ?$ where $A_1 = ?$ and $B_1 = ?$. Again, we can see **split** and **box** hiding in the shadows. When $C = ?$,

then $A_1 = ?$ which implies that $A_2 \sim A_1$ will correspond to **box**, and the premise $\text{fun}(C) = ? \rightarrow ?$ corresponds to using **split**. Thus, in this case the term $t_1 t_2$ can be converted into a term in our calculus by $(\text{split}_{(? \rightarrow ?)} t_1) (\text{box}_{A_2} t_2)$. An interesting point about this rule is that dynamically typed programs tend toward statically typed programs. However, the gradual guarantee shows that any program in the gradual type system can slide either more towards static typing or more towards dynamic typing by inserting or removing casts.

Contributions. This paper offers the following contributions:

- A new categorical model for gradual typing for functional languages. We show how to interpret Siek and Taha’s [9] gradual type system in the categorical model outlined above.
- We then extract a functional programming language called Simple Grady from the categorical model via the Curry-Howard-Lambek correspondence. This is not a gradual type system, but can be seen as an alternative core casting calculus in which Siek and Taha’s gradual type system can be translated to.
- We extend Simple Grady into a new language we call Core Grady that has natural numbers, lists, and bounded quantification. In addition, natural numbers and lists will contain an eliminator that when combined with the Y combinator yields terminating recursion without the need for Grady to explicitly contain a fixpoint operator.
- Finally, we develop a gradually typed surface language called Surface Grady and show that it satisfies the gradual guarantee.

Related work. We now give a brief summary of related work. Each of the articles discussed below can be consulted for further references.

- Abadi et al. [1] combine dynamic and static typing by adding a new type called **Dynamic** along with a new case construct for pattern matching on types. We do not add such a case construct, and as a result, show that we can obtain a surprising amount of expressivity without it. They also provide denotational models.
- Henglein [4] defines the dynamic λ -calculus by adding a new type **Dyn** to the simply typed λ -calculus and then adding primitive casting operations called **tagging** and **check-and-untag**. These new operations tag type constructors with their types. Then untagging checks to make sure the target tag matches the source tag, and if not, returns a dynamic type error. These operations can be used to build casting coercions which are very similar to our casting morphisms. We can also define **split**, **squash**, **box**, and **unbox** in terms of Henglein’s casting coercions. However, our setting is a bit more strict than his, because his “boxing” and “unboxing” operations form an isomorphism, but we show that a retract is only needed.
- As we mentioned in the introduction Siek and Taha [8] were the first to define gradual typing especially for functional languages. We show that their language can be given a straightforward categorical model in cartesian closed categories. Since their original paper introducing gradual types lots of languages have adopted it, but the term “gradual typing” started to become a catch all phrase

for any language combining dynamic and static typing. As a result of this Siek et al. [9] later refine what it means for a language to support gradual typing by specifying the necessary metatheoretic properties a gradual type system must satisfy called the gradual guarantee.

- The categorical model we give here is with respect to the core casting calculus. In future work we plan to investigate a categorical model for the surface language, and we believe that Garcia’s [3] work showing how to extract the gradual type system from a fully static type system using abstract interpretation will play a key role. Abstract interpretation uses Galois connections which can be studied as adjoints in the category of posets. Garcia shows that one can start with a static type system, and then use abstract interpretation to infer the gradually typed surface language complete with both statics and dynamics.

2 Gradual Typing

We begin by introducing a slight variation of [8]’s gradually typed functional language given by Siek et al. [9]. The syntax of the gradual type system $\lambda_{\rightarrow}^?$ is defined in the following definition.

This definition is the base syntax for every language in this paper. The typing rules are defined in Figure ?? and the type consistency relation is defined in Figure ?. The main changes of the version of $\lambda_{\rightarrow}^?$ defined here from the original due to Siek et al. [9] is that products and natural numbers have been added. The definition of products follows how casting is done for functions. So it allows casting projections of products, for example, it is reasonable for terms like $\lambda x : (? \times ?).(succ (fst x))$ to type check.

We can view gradual typing as a surface language feature much like type inference, and we give it a semantics by translating it into an annotated core. The language $\lambda_{\rightarrow}^?$ is given an operational semantics by translating it to a fully annotated core language called $\lambda_{\rightarrow}^{\Rightarrow}$. Its syntax is an extension of the syntax of $\lambda_{\rightarrow}^?$ (Definition ??) where terms are the only syntactic class that differs, and so we do not repeat the syntax of types or contexts.

The typing rules for $\lambda_{\rightarrow}^{\Rightarrow}$ can be found in Figure ??, and the reduction rules in Figure ?. The reduction relation is the usual definition of call-by-value for the simply typed λ -calculus, and so we do not give all of the rules here, but rather only the casting rules. In addition, to save space we do not define the cast insertion algorithm for $\lambda_{\rightarrow}^?$. Please see Siek et al. [9] for its definition. To make it easier for the reader to connect the reduction rules to their interpretations we give the reduction rules for $\lambda_{\rightarrow}^{\Rightarrow}$ using the terms-in-context formulation; for an introduction to this style please see Crole [2].

3 The Categorical Perspective

We now give a categorical model for $\lambda_{\rightarrow}^?$ and $\lambda_{\rightarrow}^{\Rightarrow}$, and their interpretations into the model.

Syntax:

(types)	$A, B, C, D ::= \mathbf{Unit} \mid ? \mid A \times B \mid A_1 \rightarrow A_2$
(terms)	$t ::= x \mid \mathbf{triv} \mid 0 \mid \mathbf{succ} \, t \mid \lambda x : A. t \mid t_1 \, t_2 \mid (t_1, t_2) \mid \mathbf{fst} \, t \mid \mathbf{snd} \, t$
(contexts)	$\Gamma ::= \cdot \mid x : A \mid \Gamma_1, \Gamma_2$

Typing Rules:

$\frac{x : A \in \Gamma}{\Gamma \vdash_S x : A} \text{ var}$	$\frac{}{\Gamma \vdash_S \mathbf{triv} : \mathbf{Unit}} \text{ unit}$	$\frac{}{\Gamma \vdash_S 0 : \mathbf{Nat}} \text{ zero}$
$\frac{\Gamma \vdash_S t : A \quad \mathbf{nat}(A) = \mathbf{Nat}}{\Gamma \vdash_S \mathbf{succ} \, t : \mathbf{Nat}} \text{ succ}$	$\frac{\Gamma \vdash_S t_1 : A_1 \quad \Gamma \vdash_S t_2 : A_2}{\Gamma \vdash_S (t_1, t_2) : A_1 \times A_2} \times$	
$\frac{\Gamma \vdash_S t : B \quad \mathbf{prod}(B) = A_1 \times A_2}{\Gamma \vdash_S \mathbf{fst} \, t : A_1} \times_{e_1}$	$\frac{\Gamma \vdash_S t : B \quad \mathbf{prod}(B) = A_1 \times A_2}{\Gamma \vdash_S \mathbf{snd} \, t : A_2} \times_{e_2}$	
$\frac{\Gamma, x : A \vdash_S t : B}{\Gamma \vdash_S \lambda x : A_1. t : A \rightarrow B} \rightarrow$	$\frac{\Gamma \vdash_S t_1 : C \quad \Gamma \vdash_S t_2 : A_2 \quad A_2 \sim A_1 \quad \mathbf{fun}(C) = A_1 \rightarrow B_1}{\Gamma \vdash_S t_1 \, t_2 : B_1} \rightarrow_e$	

Type Consistency:

$\frac{}{A \sim A} \text{ refl}$	$\frac{}{A \sim ?} \text{ box}$	$\frac{}{? \sim A} \text{ unbox}$	$\frac{A_1 \sim A_2 \quad B_1 \sim B_2}{A_1 \rightarrow B_1 \sim A_2 \rightarrow B_2} \rightarrow$
$\frac{A_1 \sim A_2 \quad B_1 \sim B_2}{A_1 \times B_1 \sim A_2 \times B_2} \times$			

 Fig. 1. The gradually simply typed λ -calculus: $\lambda_{\rightarrow}^?$

3.1 The Categorical Model

The model we develop here builds on the seminal work of Lambek [5] and Scott [7]. Lambek [5] showed that the typed λ -calculus can be modeled by a cartesian closed category. In the same volume as Lambek, Scott essentially showed that the untyped λ -calculus is actually typed. That is, typed theories are more fundamental than untyped ones. He accomplished this by adding a single type, $?$, and two functions $\mathbf{squash} : (? \rightarrow ?) \rightarrow ?$ and $\mathbf{split} : ? \rightarrow (? \rightarrow ?)$, such that, $\mathbf{squash}; \mathbf{split} = \mathbf{id} : (? \rightarrow ?) \rightarrow (? \rightarrow ?)$. At this point he was able to translate the untyped λ -calculus into this untyped one. Categorically, he modeled \mathbf{split} and \mathbf{squash} as the morphisms in a retract within a cartesian closed category – the same model as typed λ -calculus.

Definition 3.1 Suppose \mathcal{C} is a category. Then an object A is a **retract** of an object B if there are morphisms $i : A \rightarrow B$ and $r : B \rightarrow A$ such that $i; r = \mathbf{id}_A$.

Thus, $? \rightarrow ?$ is a retract of $?$, but we also require that $? \times ?$ be a retract of $?$; this is not new, see Lambek and Scott [6].

Since all of the languages we are studying here contain the natural numbers we must be able to interpret them into our model. We give a novel approach to modeling the natural numbers with their (non-recursive) eliminator using what we call a Scott natural number object. Now the natural number eliminator is not part

Syntax:

(Atomic Types) $T ::= \text{Unit} \mid \text{Nat}$ (values) $v ::= \lambda x : A. t$
 (Ground Types) $R ::= T \mid ? \rightarrow ?$ (terms) $t ::= \dots \mid t : A \Rightarrow B$

Typing Rules:

$$\begin{array}{c}
 \frac{x : A \in \Gamma}{\Gamma \vdash_{\mathcal{C}} x : A} \text{var} \quad \frac{}{\Gamma \vdash_{\mathcal{C}} \text{triv} : \text{Unit}} \text{unit} \quad \frac{}{\Gamma \vdash_{\mathcal{C}} 0 : \text{Nat}} \text{zero} \quad \frac{\Gamma \vdash_{\mathcal{C}} t : \text{Nat}}{\Gamma \vdash_{\mathcal{C}} \text{succ } t : \text{Nat}} \text{succ} \\
 \\
 \frac{\Gamma \vdash_{\mathcal{C}} t_1 : A_1 \quad \Gamma \vdash_{\mathcal{C}} t_2 : A_2}{\Gamma \vdash_{\mathcal{C}} (t_1, t_2) : A_1 \times A_2} \times \quad \frac{\Gamma \vdash_{\mathcal{C}} t : A_1 \times A_2}{\Gamma \vdash_{\mathcal{C}} \text{fst } t : A_1} \times_{e_1} \quad \frac{\Gamma \vdash_{\mathcal{C}} t : A_1 \times A_2}{\Gamma \vdash_{\mathcal{C}} \text{snd } t : A_2} \times_{e_2} \\
 \\
 \frac{\Gamma, x : A \vdash_{\mathcal{C}} t : B}{\Gamma \vdash_{\mathcal{C}} \lambda x : A. t : A \rightarrow B} \rightarrow \quad \frac{\Gamma \vdash_{\mathcal{C}} t_1 : A \rightarrow B \quad \Gamma \vdash_{\mathcal{C}} t_2 : A}{\Gamma \vdash_{\mathcal{C}} t_1 t_2 : B} \rightarrow_e \\
 \\
 \frac{\Gamma \vdash_{\mathcal{C}} t : A \quad A \sim B}{\Gamma \vdash_{\mathcal{C}} (t : A \Rightarrow B) : B} \text{cast}
 \end{array}$$

Reduction Relation:

$$\begin{array}{c}
 \frac{\Gamma \vdash_{\mathcal{C}} v : A}{\Gamma \vdash v \rightsquigarrow v : A} \text{values} \quad \frac{\Gamma \vdash_{\mathcal{C}} v : T}{\Gamma \vdash v : T \Rightarrow T \rightsquigarrow v : T} \text{id-atom} \quad \frac{\Gamma \vdash_{\mathcal{C}} v : ?}{\Gamma \vdash v : ? \Rightarrow ? \rightsquigarrow v : ?} \text{id-U} \\
 \\
 \frac{\Gamma \vdash_{\mathcal{C}} v : R}{\Gamma \vdash v : R \Rightarrow ? \Rightarrow R \rightsquigarrow v : R} \text{succeed} \\
 \\
 \frac{\Gamma \vdash_{\mathcal{C}} v_1 : A_1 \rightarrow B_1 \quad \Gamma \vdash_{\mathcal{C}} v_2 : A_2 \quad (A_1 \rightarrow B_1) \sim (A_2 \rightarrow B_2)}{\Gamma \vdash (v_1 : (A_1 \rightarrow B_1) \Rightarrow (A_2 \rightarrow B_2)) v_2 \rightsquigarrow v_1 (v_2 : A_2 \Rightarrow A_1) : B_1 \Rightarrow B_2 : B_2} \text{arrow} \\
 \\
 \frac{\Gamma \vdash_{\mathcal{C}} v : A \quad A \sim R \quad A \neq R \quad A \neq ?}{\Gamma \vdash v : A \Rightarrow ? \rightsquigarrow v : A \Rightarrow R \Rightarrow ? : ?} \text{expand}_1 \\
 \\
 \frac{\Gamma \vdash_{\mathcal{C}} v : ? \quad A \sim R \quad A \neq R \quad A \neq ?}{\Gamma \vdash v : ? \Rightarrow A \rightsquigarrow v : ? \Rightarrow R \Rightarrow A : A} \text{expand}_2
 \end{array}$$

 Fig. 2. The core casting calculus: $\lambda_{\rightarrow}^{\Rightarrow}$

of $\lambda_{\rightarrow}^?$ or $\lambda_{\rightarrow}^{\Rightarrow}$, but we want Grady to contain it, and Grady will directly correspond to the model.

Definition 3.2 Suppose \mathcal{C} is a cartesian closed category. A **Scott natural number object (SNNO)** is an object Nat of \mathcal{C} and morphisms $z : 1 \rightarrow \text{Nat}$ and $\text{succ} : \text{Nat} \rightarrow \text{Nat}$ of \mathcal{C} , such that, for any morphisms $f : Y \rightarrow X$ and $g : Y \times \text{Nat} \rightarrow X$ of \mathcal{C} there is a unique morphism $\text{case}_X : Y \times \text{Nat} \rightarrow X$ making the following diagrams commute:

$$\begin{array}{ccccc}
 Y \times \text{Nat} & \xrightarrow{\text{id}_Y \times z} & Y \times \text{Nat} & \xleftarrow{\text{id}_Y \times \text{succ}} & Y \times \text{Nat} \\
 & \searrow \pi_1; f & \downarrow \text{case}_X & \swarrow g & \\
 & & X & &
 \end{array}$$

Informally, the two diagrams essentially assert that we can define case_X as follows:

$$\text{case}_X y 0 = f y \quad \text{case}_X y (\text{succ } x) = g y x$$

This formalization of natural numbers is inspired by the definition of Scott Numerals [?] where the notion of a case distinction is built into the encoding.

So far we can model the untyped and the typed λ -calculi within a cartesian closed category, but we do not have any way of moving typed data into the untyped part and vice versa. To accomplish this we add two new morphisms $\text{box}_C : C \longrightarrow ?$ and $\text{unbox}_C : ? \longrightarrow C$ such that each atomic type, C , is a retract of $?$. This enforces that the only time we can really consider something as typed is if it were boxed up in the first place.

Now we combine everything we have discussed so far to obtain the categorical model.

Definition 3.3 A **gradual λ -model**, $(\mathcal{T}, \mathcal{C}, ?, \mathsf{T}, \text{split}, \text{squash}, \text{box}, \text{unbox})$, where \mathcal{T} is a discrete category with at least two objects **Nat** and **Unit**, \mathcal{C} is a cartesian closed category with a SNNO, $(\mathcal{C}, ?, \text{split}, \text{squash})$ is an untyped λ -model, $\mathsf{T} : \mathcal{T} \longrightarrow \mathcal{C}$ is an embedding – a full and faithful functor that is injective on objects – and for every object A of \mathcal{T} there are morphisms $\text{box}_A : TA \longrightarrow ?$ and $\text{unbox}_A : ? \longrightarrow TA$ making TA a retract of $?$.

We call the category \mathcal{T} the category of atomic types. We call an object, A , **atomic** iff there is some object A' in \mathcal{T} such that $A = \mathsf{T}A'$. Note that we do not consider $?$ an atomic type. The model really is the cartesian closed category \mathcal{C} , but it is extended with the structure of both the typed and the untyped λ -calculus with the ability to cast data.

Interpreting the typing rules for $\lambda_{\rightarrow}^?$ will require the interpretation of type consistency. Thus, we must be able to cast any type A to $?$, but as stated the model only allows atomic types to be casted. It turns out that this can be lifted to any type.

We call any morphism defined completely in terms of id , the functors $- \times -$ and $- \rightarrow -$, split and squash , and box and unbox a **casting morphism**. To cast any type A to $?$ we will build casting morphisms that first take the object A to its skeleton, and then takes the skeleton to $?$.

Definition 3.4 Suppose $(\mathcal{T}, \mathcal{C}, ?, \mathsf{T}, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model. Then the **skeleton** of an object A of \mathcal{C} is an object S that is constructed by replacing each atomic type in A with $?$. Given an object A we denote its skeleton by $\text{skeleton } A$.

One should think of the skeleton of an object as the supporting type structure of the object, but we do not know what kind of data is actually in the structure. For example, the skeleton of the object **Nat** is $?$, and the skeleton of $(\text{Nat} \times \text{Unit}) \rightarrow \text{Nat} \rightarrow \text{Nat}$ is $(? \times ?) \rightarrow ? \rightarrow ?$.

The next definition defines a means of constructing a casting morphism that casts a type A to its skeleton and vice versa. This definition is by mutual recursion on the input type.

Definition 3.5 Suppose $(\mathcal{T}, \mathcal{C}, ?, \mathsf{T}, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model. Then for any object A whose skeleton is S we define the morphisms $\widehat{\text{box}}_A : A \longrightarrow S$

and $\widehat{\text{unbox}}_A : S \longrightarrow A$ by mutual recursion on A as follows:

$$\begin{array}{c|c}
 \widehat{\text{box}}_A = \text{box}_A & \widehat{\text{unbox}}_A = \text{unbox}_A \\
 \text{when } A \text{ is atomic} & \text{when } A \text{ is atomic} \\
 \widehat{\text{box}}_? = \text{id}_? & \widehat{\text{unbox}}_? = \text{id}_? \\
 \widehat{\text{box}}_{(A_1 \rightarrow A_2)} = \widehat{\text{unbox}}_{A_1} \rightarrow \widehat{\text{box}}_{A_2} & \widehat{\text{unbox}}_{(A_1 \rightarrow A_2)} = \widehat{\text{box}}_{A_1} \rightarrow \widehat{\text{unbox}}_{A_2} \\
 \widehat{\text{box}}_{(A_1 \times A_2)} = \widehat{\text{box}}_{A_1} \times \widehat{\text{box}}_{A_2} & \widehat{\text{unbox}}_{(A_1 \times A_2)} = \widehat{\text{unbox}}_{A_1} \times \widehat{\text{unbox}}_{A_2}
 \end{array}$$

The definition of both $\widehat{\text{box}}$ or $\widehat{\text{unbox}}$ uses the functor $- \rightarrow - : \mathcal{C}^{\text{op}} \times \mathcal{C} \longrightarrow \mathcal{C}$ which is contravariant in its first argument, and thus, in that contravariant position we must make a recursive call to the opposite function, and hence, they must be mutually defined. Every call to either $\widehat{\text{box}}$ or $\widehat{\text{unbox}}$ in the previous definition is on a smaller object than the input object. Thus, their definitions are well founded. Furthermore, $\widehat{\text{box}}$ and $\widehat{\text{unbox}}$ form a retract between A and S .

Lemma 3.6 (Boxing and Unboxing Lifted Retract) *Suppose $(\mathcal{T}, \mathcal{C}, ?, \top, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model. Then for any object A , $\widehat{\text{box}}_A; \widehat{\text{unbox}}_A = \text{id}_A : A \longrightarrow A$.*

Proof. This proof holds by induction on the form A . Please see Appendix B.1 for the complete proof. \square

As an example, suppose we wanted to cast the type $(\text{Nat} \times ?) \rightarrow \text{Nat}$ to its skeleton $(? \times ?) \rightarrow ?$. Then we can obtain a casting morphisms that will do this as follows:

$$\begin{aligned}
 \widehat{\text{box}}_{((\text{Nat} \times ?) \rightarrow \text{Nat})} &= \widehat{\text{unbox}}_{(\text{Nat} \times ?)} \rightarrow \widehat{\text{box}}_{\text{Nat}} \\
 &= (\widehat{\text{unbox}}_{\text{Nat}} \times \widehat{\text{unbox}}_?) \rightarrow \widehat{\text{box}}_{\text{Nat}} \\
 &= (\text{unbox}_{\text{Nat}} \times \text{id}_?) \rightarrow \text{box}_{\text{Nat}}
 \end{aligned}$$

We can also cast a morphism $A \xrightarrow{f} B$ to a morphism

$$S_1 \xrightarrow{\widehat{\text{unbox}}_A} A \xrightarrow{f} B \xrightarrow{\widehat{\text{box}}_B} S_2$$

where $S_1 = \text{skeleton } A$ and $S_2 = \text{skeleton } B$. Now if we have a second

$$S_2 \xrightarrow{\widehat{\text{unbox}}_B} B \xrightarrow{g} C \xrightarrow{\widehat{\text{box}}_C} S_3$$

then their composition reduces to composition at the typed level:

The right most diagram commutes because B is a retract of S_2 , and the left unannotated arrow is the composition $\widehat{\text{unbox}}_A; f; g; \widehat{\text{box}}_C$. This tells us that we have a functor $S : \mathcal{C} \longrightarrow \mathcal{S}$:

$$\begin{aligned}
 SA &= \text{skeleton } A \\
 S(f : A \longrightarrow B) &= \widehat{\text{unbox}}_A; f; \widehat{\text{box}}_B
 \end{aligned}$$

where \mathcal{S} is the full subcategory of \mathcal{C} consisting of the skeletons and morphisms between them, that is, \mathcal{S} is a cartesian closed category with one basic object $?$ such that $(\mathcal{S}, ?, \text{split}, \text{squash})$ is an untyped λ -model. The following turns out to be true.

Lemma 3.7 (S is faithful) *Suppose $(\mathcal{T}, \mathcal{C}, ?, \top, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model, and $(\mathcal{S}, ?, \text{split}, \text{squash})$ is the category of skeletons. Then the functor $S : \mathcal{C} \longrightarrow \mathcal{S}$ is faithful.*

Proof. This proof follows from the definition S and Lemma 3.6. For the full proof see Appendix B.2. \square

Thus, we can think of the functor S as an injection of the typed world into the untyped one.

Now that we can cast any type into its skeleton we must show that every skeleton can be cast to $?$. We do this similarly to the above and lift split and squash to arbitrary skeletons.

Definition 3.8 Suppose $(\mathcal{S}, ?, \text{split}, \text{squash})$ is the category of skeletons. Then for any skeleton S we define the morphisms $\widehat{\text{squash}}_S : S \longrightarrow ?$ and $\widehat{\text{split}}_S : ? \longrightarrow S$ by mutual recursion on S as follows:

$$\begin{array}{l|l} \widehat{\text{squash}}_? = \text{id}_? & \widehat{\text{split}}_? = \text{id}_? \\ \widehat{\text{squash}}_{(S_1 \rightarrow S_2)} = (\widehat{\text{split}}_{S_1} \rightarrow \widehat{\text{squash}}_{S_2}); \text{squash}_{? \rightarrow ?} & \widehat{\text{split}}_{(S_1 \rightarrow S_2)} = \text{split}_{? \rightarrow ?}; (\widehat{\text{squash}}_{S_1} \rightarrow \widehat{\text{split}}_{S_2}) \\ \widehat{\text{squash}}_{(S_1 \times S_2)} = (\widehat{\text{squash}}_{S_1} \times \widehat{\text{squash}}_{S_2}); \text{squash}_{? \times ?} & \widehat{\text{split}}_{(S_1 \times S_2)} = \text{split}_{? \times ?}; (\widehat{\text{split}}_{S_1} \times \widehat{\text{split}}_{S_2}) \end{array}$$

As an example we will construct the casting morphism that casts the skeleton $(? \times ?) \rightarrow ?$ to $?$:

$$\begin{aligned} \widehat{\text{squash}}_{(? \times ?) \rightarrow ?} &= (\widehat{\text{split}}_{? \times ?} \rightarrow \widehat{\text{squash}}_?); \text{squash}_{? \rightarrow ?} \\ &= (\text{split}_{? \times ?}; (\widehat{\text{split}}_? \times \widehat{\text{split}}_?)) \rightarrow \widehat{\text{squash}}_?; \text{squash}_{? \rightarrow ?} \\ &= ((\text{split}_{? \times ?}; (\text{id}_? \times \text{id}_?)) \rightarrow \text{id}_?); \text{squash}_{? \rightarrow ?} \\ &= (\text{split}_{? \times ?} \rightarrow \text{id}_?); \text{squash}_{? \rightarrow ?} \end{aligned}$$

The morphisms $\widehat{\text{split}}_S$ and $\widehat{\text{squash}}_S$ form a retract between S and $?$.

Lemma 3.9 (Splitting and Squashing Lifted Retract) *Suppose $(\mathcal{S}, ?, \text{split}, \text{squash})$ is the category of skeletons. Then for any skeleton S ,*

$$\widehat{\text{squash}}_S; \widehat{\text{split}}_S = \text{id}_S : S \longrightarrow S$$

Proof. The proof is similar to the proof of the boxing and unboxing lifted retract (Lemma 3.6). \square

There is also a faithful functor from \mathcal{S} to \mathcal{U} where \mathcal{U} is the full subcategory of \mathcal{S} that consists of the single object $?$ and all its morphisms between it:

$$\begin{aligned} \mathcal{U}\mathcal{S} &= ? \\ \mathcal{U}(f : S_1 \longrightarrow S_2) &= \widehat{\text{split}}_{S_1}; f; \widehat{\text{squash}}_{S_2} \end{aligned}$$

This finally implies that there is a functor $\mathcal{C} : \mathcal{C} \longrightarrow \mathcal{U}$ that injects all of \mathcal{C} into the object $?$.

Lemma 3.10 (Casting to $?$) *Suppose $(\mathcal{T}, \mathcal{C}, ?, \mathsf{T}, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model, $(\mathcal{S}, ?, \text{split}, \text{squash})$ is the full subcategory of skeletons, and $(\mathcal{U}, ?)$ is the full subcategory containing only $?$ and its morphisms. Then there is a faithful functor $\mathcal{C} = \mathcal{C} \xrightarrow{\mathcal{S}} \mathcal{S} \xrightarrow{\mathcal{U}} \mathcal{U}$.*

In a way we can think of $\mathcal{C} : \mathcal{C} \longrightarrow \mathcal{U}$ as a forgetful functor. It forgets the type information.

Getting back the typed information is harder. There is no nice functor from \mathcal{U} to \mathcal{C} , because we need more information. However, given a type A we can always obtain a casting morphism from $?$ to A by $(\widehat{\text{split}}_{(\text{skeleton } A)}); (\widehat{\text{unbox}}_A) : ? \longrightarrow A$. Finally, we have the following result.

Lemma 3.11 (Casting Morphisms to $?$) *Suppose $(\mathcal{T}, \mathcal{C}, ?, \mathsf{T}, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model, and A is an object of \mathcal{C} . Then there exists casting morphisms from A to $?$ and vice versa that make A a retract of $?$.*

Proof. The two morphisms are as follows:

$$\text{Box}_A := \widehat{\text{box}}_A; \widehat{\text{squash}}_{(\text{skeleton } A)} : A \longrightarrow ?$$

$$\text{Unbox}_A := \widehat{\text{split}}_{(\text{skeleton } A)}; \widehat{\text{unbox}}_A : ? \longrightarrow A$$

The fact the these form a retract between A and $?$ holds by Lemma 3.6 and Lemma 3.9. \square

3.2 The Interpretation

In this section we show how to interpret $\lambda_{\rightarrow}^?$ and $\lambda_{\rightarrow}^{\Rightarrow}$ into the categorical model given in the previous section. We complete the three steps summarized above. We will show how to interpret the typing of the former into the model, and then show how to do the same for the latter, furthermore, we show that reduction can be interpreted into the model as well, thus concluding soundness for $\lambda_{\rightarrow}^{\Rightarrow}$ with respect to our model.

First, we must give the interpretation of types and contexts, but this interpretation is obvious, because we have been making sure to match the names of types and objects throughout this paper.

Definition 3.12 Suppose $(\mathcal{T}, \mathcal{C}, ?, \top, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model. Then we define the interpretation of types into \mathcal{C} as follows:

$$\begin{aligned} \llbracket \text{Unit} \rrbracket &= 1 \\ \llbracket \text{Nat} \rrbracket &= \text{Nat} \\ \llbracket ? \rrbracket &= ? \\ \llbracket A_1 \rightarrow A_2 \rrbracket &= \llbracket A_1 \rrbracket \rightarrow \llbracket A_2 \rrbracket \\ \llbracket A_1 \times A_2 \rrbracket &= \llbracket A_1 \rrbracket \times \llbracket A_2 \rrbracket \end{aligned}$$

We extend this interpretation to typing contexts as follows:

$$\begin{aligned} \llbracket \cdot \rrbracket &= 1 \\ \llbracket \Gamma, x : A \rrbracket &= \llbracket \Gamma \rrbracket \times \llbracket A \rrbracket \end{aligned}$$

Throughout the remainder of this paper we will drop the interpretation symbols around types.

Before we can interpret the typing rules of $\lambda_{\rightarrow}^?$ and $\lambda_{\rightarrow}^{\Rightarrow}$ we must show how to interpret the consistency relation from Figure ???. These will correspond to casting morphisms.

Lemma 3.13 (Type Consistency in the Model) *Suppose $(\mathcal{T}, \mathcal{C}, ?, \top, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model, and $A \sim B$ for some types A and B . Then there are two casting morphisms $c_1 : A \longrightarrow B$ and $c_2 : B \longrightarrow A$.*

Proof. This proof holds by induction on the form $A \sim B$ using the morphisms $\text{Box}_A : A \longrightarrow ?$ and $\text{Unbox}_A : ? \longrightarrow A$. Please see Appendix B.3 for the complete proof. \square

Corollary 3.14 *Suppose $(\mathcal{T}, \mathcal{C}, ?, \top, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model. Then we know the following:*

- i. *If $A \sim A$, then $c_1 = c_2 = \text{id}_A : A \longrightarrow A$.*
- ii. *If $A \sim ?$, then there are casting morphisms:*

$$\begin{aligned} c_1 &= \text{Box}_A : A \longrightarrow ? \\ c_2 &= \text{Unbox}_A : ? \longrightarrow A \end{aligned}$$

- iii. *If $? \sim A$, then there are casting morphisms:*

$$\begin{aligned} c_1 &= \text{Unbox}_A : ? \longrightarrow A \\ c_2 &= \text{Box}_A : A \longrightarrow ? \end{aligned}$$

iv. If $A_1 \rightarrow B_1 \sim A_2 \rightarrow B_2$, then there are casting morphisms:

$$\begin{aligned} c &= c_1 \rightarrow c_2 : (A_1 \rightarrow B_1) \longrightarrow (A_2 \rightarrow B_2) \\ c' &= c_3 \rightarrow c_4 : (A_2 \rightarrow B_2) \longrightarrow (A_1 \rightarrow B_1) \end{aligned}$$

where $c_1 : A_2 \longrightarrow A_1$ and $c_2 : B_1 \longrightarrow B_2$, and $c_3 : A_1 \longrightarrow A_2$ and $c_4 : B_2 \longrightarrow B_1$.

v. If $A_1 \times B_1 \sim A_2 \times B_2$, then there are casting morphisms:

$$\begin{aligned} c &= c_1 \times c_2 : (A_1 \times B_1) \longrightarrow (A_2 \times B_2) \\ c' &= c_3 \times c_4 : (A_2 \times B_2) \longrightarrow (A_1 \times B_1) \end{aligned}$$

where $c_1 : A_1 \longrightarrow A_2$ and $c_2 : B_1 \longrightarrow B_2$, and $c_3 : A_2 \longrightarrow A_1$ and $c_4 : B_2 \longrightarrow B_1$.

Proof. This proof holds by the construction of the casting morphisms from the proof of the previous result, and the fact that the type consistency rules are unique for each type. \square

Showing that both c_1 and c_2 exist corresponds to the fact that $A \sim B$ is symmetric. But, this interpretation is an over approximation of type consistency, because type consistency is not transitive, but function composition is. Leaving type consistency implicit in the model just does not make good sense categorically, because it would break composition. For example, if we have morphisms $f : A \longrightarrow ?$ and $g : B \longrightarrow C$, then if we implicitly allowed $?$ to be cast to B , then we could compose these two morphisms, but this does not fit the definition of a category, because it requires the target of f to match the source of g , but this just is not the case. Thus, the explicit cast must be used to obtain $f; \text{unbox}_B; g$.

At this point we have everything we need to show our main result which is that typing in both $\lambda_{\rightarrow}^?$ and $\lambda_{\rightarrow}^{\rightarrow}$, and evaluation in $\lambda_{\rightarrow}^{\rightarrow}$ can be interpreted into the categorical model.

Theorem 3.15 (Interpretation of Typing) *Suppose $(\mathcal{T}, \mathcal{C}, ?, \top, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model.*

- i. If $\Gamma \vdash_{\mathcal{S}} t : A$, then there is a morphism $\llbracket t \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow A$ in \mathcal{C} .
- ii. If $\Gamma \vdash_{\mathcal{C}} t : A$, then there is a morphism $\llbracket t \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow A$ in \mathcal{C} .

Proof. Both parts of the proof hold by induction on the form of the assumed typing derivation, and uses most of the results we have developed up to this point. Please see Appendix B.4 for the complete proof. \square

Theorem 3.16 (Interpretation of Evaluation) *Suppose $(\mathcal{T}, \mathcal{C}, ?, \top, \text{split}, \text{squash}, \text{box}, \text{unbox})$ is a gradual λ -model. If $\Gamma \vdash t_1 \rightsquigarrow t_2 : A$, then $\llbracket t_1 \rrbracket = \llbracket t_2 \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow A$.*

Proof. This proof holds by induction on the form of $\Gamma \vdash t_1 \rightsquigarrow t_2 : A$, and uses Theorem 3.15, Lemma 3.13, and Corollary 3.14. Please see Appendix B.5 for the complete proof. \square

$\frac{x : A \in \Gamma}{\Gamma \vdash x : A} \text{var}$	$\frac{}{\Gamma \vdash \text{box}_T : T \rightarrow ?} \text{box}$	$\frac{}{\Gamma \vdash \text{unbox}_T : ? \rightarrow T} \text{unbox}$
$\frac{}{\Gamma \vdash \text{squash}_U : U \rightarrow ?} \text{squash}$	$\frac{}{\Gamma \vdash \text{split}_U : ? \rightarrow U} \text{split}$	
$\frac{}{\Gamma \vdash \text{triv} : \text{Unit}} \text{unit}$	$\frac{}{\Gamma \vdash 0 : \text{Nat}} \text{zero}$	$\frac{\Gamma \vdash t : \text{Nat}}{\Gamma \vdash \text{succ } t : \text{Nat}} \text{succ}$
$\frac{\Gamma \vdash t : \text{Nat}}{\Gamma \vdash \text{case } t \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 : A} \text{Nat}_e$	$\frac{\Gamma \vdash t_1 : A_1 \quad \Gamma \vdash t_2 : A_2}{\Gamma \vdash (t_1, t_2) : A_1 \times A_2} \text{pair}$	
$\frac{\Gamma \vdash t : A_1 \times A_2}{\Gamma \vdash \text{fst } t : A_1} \text{fst}$	$\frac{\Gamma \vdash t : A_1 \times A_2}{\Gamma \vdash \text{snd } t : A_2} \text{snd}$	$\frac{\Gamma, x : A \vdash t : B}{\Gamma \vdash \lambda x : A. t : A \rightarrow B} \text{lam}$
$\frac{\Gamma \vdash t_1 : A \rightarrow B \quad \Gamma \vdash t_2 : A}{\Gamma \vdash t_1 t_2 : B} \text{app}$		

Fig. 3. Typing rules for Grady

4 Simply Typed Core Grady

Just as the simply typed λ -calculus corresponds to cartesian closed categories our categorical model has a corresponding type theory we call Grady. It consists of all of the structure found in the model. Its syntax is an extension of the syntax for $\lambda_{\rightarrow}^?$.

Definition 4.1 Syntax for Grady:

(basic skeletons) $U ::= ? \rightarrow ? \mid ? \times ?$

(skeletons) $S ::= ? \mid S_1 \times S_2 \mid S_1 \rightarrow S_2$

(atomic types) $C ::= \text{Unit} \mid \text{Nat}$

(terms) $t ::= \dots \mid \text{split}_U \mid \text{squash}_U \mid \text{box}_C \mid \text{unbox}_C \mid \text{case } t \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2$

(natural numbers) $n ::= 0 \mid \text{succ } n$

(simple values) $s ::= x \mid \text{triv} \mid n \mid \text{squash}_U \mid \text{split}_U \mid \text{box}_C \mid \text{unbox}_C$

The types of Grady are the same as the types of $\lambda_{\rightarrow}^?$ (Definition ??), in addition, it encompasses all the terms of $\lambda_{\rightarrow}^?$, and so we do not repeat either of them here. The typing rules for Grady can be found in Figure 3 and its reduction rules can be found in Figure 4.

$$\begin{array}{c}
 \frac{\Gamma \vdash s : A}{\Gamma \vdash s \rightsquigarrow s : A} \text{values} \qquad \frac{\Gamma \vdash t : T}{\Gamma \vdash \text{unbox}_T(\text{box}_T t) \rightsquigarrow t : T} \text{retract}_1 \\
 \\
 \frac{\Gamma \vdash t : U}{\Gamma \vdash \text{split}_U(\text{squash}_U t) \rightsquigarrow t : U} \text{retract}_2 \qquad \frac{\Gamma, x : A_1 \vdash t_1 : A_2 \quad \Gamma \vdash t_2 : A_1}{\Gamma \vdash (\lambda x : A_1. t_1) v \rightsquigarrow [t_2/x] t_2 : A_2} \beta \\
 \\
 \frac{\Gamma \vdash t_1 : A_1 \quad \Gamma \vdash t_2 : A_2}{\Gamma \vdash \text{fst}(t_1, t_2) \rightsquigarrow t_1 : A_1} \times_{e_1} \qquad \frac{\Gamma \vdash t_1 : A_1 \quad \Gamma \vdash t_2 : A_2}{\Gamma \vdash \text{snd}(t_1, t_2) \rightsquigarrow t_2 : A_2} \times_{e_2} \\
 \\
 \frac{\Gamma \vdash t \rightsquigarrow t' : \text{Nat}}{\Gamma \vdash \text{succ } t \rightsquigarrow \text{succ } t' : \text{Nat}} \text{succ} \\
 \\
 \frac{\Gamma \vdash t_1 : A \quad \Gamma, x : \text{Nat} \vdash t_2 : A}{\Gamma \vdash \text{case } 0 \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 \rightsquigarrow t_1 : A} \text{Nat}_{e_0} \\
 \\
 \frac{\Gamma \vdash t : \text{Nat} \quad \Gamma \vdash t_1 : A \quad \Gamma, x : \text{Nat} \vdash t_2 : A}{\Gamma \vdash \text{case } (\text{succ } t) \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 \rightsquigarrow [t/x] t_2 : A} \text{Nat}_{e_1} \\
 \\
 \frac{\Gamma \vdash t \rightsquigarrow t' : \text{Nat} \quad \Gamma \vdash t_1 : A \quad \Gamma, x : \text{Nat} \vdash t_2 : A}{\Gamma \vdash \text{case } t \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 \rightsquigarrow \text{case } t' \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 : A} \text{case}_1 \\
 \\
 \frac{\Gamma \vdash t_1 \rightsquigarrow t'_1 : A_1 \rightarrow A_2 \quad \Gamma \vdash t_2 : A_1}{\Gamma \vdash t_1 t_2 \rightsquigarrow t'_1 t_2 : A_2} \rightarrow_{e_1} \\
 \\
 \frac{\Gamma \vdash v : A_1 \rightarrow A_2 \quad \Gamma \vdash t \rightsquigarrow t' : A_1}{\Gamma \vdash v t \rightsquigarrow v t' : A_2} \rightarrow_{e_2} \qquad \frac{\Gamma \vdash t \rightsquigarrow t' : A_1 \times A_2}{\Gamma \vdash \text{fst } t \rightsquigarrow \text{fst } t' : A_1} \text{fst} \\
 \\
 \frac{\Gamma \vdash t \rightsquigarrow t' : A_1 \times A_2}{\Gamma \vdash \text{snd } t \rightsquigarrow \text{snd } t' : A_2} \text{snd} \qquad \frac{\Gamma \vdash t_1 \rightsquigarrow t'_1 : A_1 \quad \Gamma \vdash t_2 : A_2}{\Gamma \vdash (t_1, t_2) \rightsquigarrow (t'_1, t_2) : A_1 \times A_2} \times_1 \\
 \\
 \frac{\Gamma \vdash t_1 : A_1 \quad \Gamma \vdash t_2 \rightsquigarrow t'_2 : A_2}{\Gamma \vdash (t_1, t_2) \rightsquigarrow (t_1, t'_2) : A_1 \times A_2} \times_2
 \end{array}$$

Fig. 4. Reduction rules for Grady

Just as we did for the categorical model (Lemma 3.11) we can lift box_C and unbox_C to arbitrary type.

Lemma 4.2 (Syntactic Box_A and Unbox_A) *Given any type A there are functions Box_A and Unbox_A such that the following typing rules are admissible:*

$$\frac{}{\Gamma \vdash \text{Box}_A : A \rightarrow ?} \text{Box} \quad \frac{}{\Gamma \vdash \text{Unbox}_A : ? \rightarrow A} \text{Unbox}$$

Furthermore, the following reduction rule is admissible:

$$\frac{\Gamma \vdash t : A}{\Gamma \vdash \text{Unbox}_A (\text{Box}_A t) \rightsquigarrow t : A} \text{retract}_3$$

Proof. The functions Box_A and Unbox_A can be defined using the construction from the categorical model, e.g. Definition 3.5, Definition 3.8, and Lemma 3.11. However, the categorical notions of composition, identity, and the functors $- \rightarrow -$ and $- \times -$ must be defined as meta-functions first, but after they are, then the same constructions apply. Please see Appendix B.6 for the constructions. \square

Perhaps unsurprisingly, due to our results with respect to the categorical model, we can use the previous result to construct a type-directed translation of both $\lambda_{\rightarrow}^?$ and $\lambda_{\rightarrow}^{\Rightarrow}$ into Grady.

Lemma 4.3 (Translations)

- i. If $\Gamma \vdash t : A$ hold in either $\lambda_{\rightarrow}^?$ or $\lambda_{\rightarrow}^{\Rightarrow}$, then there exists a term t' such that $\Gamma \vdash t' : A$ holds in Grady.
- ii. If $\Gamma \vdash t_1 \rightsquigarrow t_2 : A$ holds in $\lambda_{\rightarrow}^{\Rightarrow}$, then $\Gamma \vdash t'_1 \rightsquigarrow t'_2 : A$ holds in Grady, where $\Gamma \vdash t'_1 : A$ and $\Gamma \vdash t'_2 : A$ are both the corresponding Grady terms.

Proof. The proof of this result is similar to the proof that both $\lambda_{\rightarrow}^?$ and $\lambda_{\rightarrow}^{\Rightarrow}$ can be interpreted into the categorical model, Theorem 3.15 and Theorem 3.16, and thus, we do not give the full proof. The proof of part one holds by induction on $\Gamma \vdash t : A$, and using the realization that if $A \sim B$ for some types A and B then there are casting terms $\cdot \vdash c_1 : A \rightarrow B$ and $\cdot \vdash c_2 : B \rightarrow A$ following the proof of Lemma 3.13. The proof of part two holds by induction on $\Gamma \vdash t_1 \rightsquigarrow t_2 : A$ making use of part one; it is similar to the proof of Theorem 3.16. \square

4.1 Exploiting the Untyped λ -Calculus

Having the untyped λ -calculus along side the typed λ -calculus can be a lot of fun. This section can be seen from two perspectives: it gives a number of examples in Grady, and shows several ways the typed and untyped fragments can be mixed.

Michael is writing this section.

- Church Encoded Data
- Y-combinator and the natural number eliminator, e.g. terminating recursion on natural numbers

$$\begin{array}{c}
 \frac{\Gamma \vdash A : \star}{\Gamma \vdash A \lesssim A} \text{refl} \quad \frac{\Gamma \vdash A : \star}{\Gamma \vdash A \lesssim \top} S_Top \quad \frac{X <: A' \in \Gamma \quad \Gamma \vdash A' \sim A}{\Gamma \vdash X \lesssim A} \text{var} \\
 \\
 \frac{\Gamma \vdash A \lesssim \mathbb{S}}{\Gamma \vdash A \lesssim ?} \text{box} \quad \frac{\Gamma \vdash A \lesssim \mathbb{S}}{\Gamma \vdash ? \lesssim A} \text{unbox} \quad \frac{\Gamma \text{Ok}}{\Gamma \vdash ? \lesssim \mathbb{S}} S_USL \\
 \\
 \frac{\Gamma \text{Ok}}{\Gamma \vdash \text{Nat} \lesssim \mathbb{S}} S_NatSL \quad \frac{\Gamma \text{Ok}}{\Gamma \vdash \text{Unit} \lesssim \mathbb{S}} S_UnitSL \quad \frac{\Gamma \vdash A \lesssim \mathbb{S}}{\Gamma \vdash \text{List } A \lesssim \mathbb{S}} S_ListSL \\
 \\
 \frac{\Gamma \vdash A \lesssim \mathbb{S} \quad \Gamma \vdash B \lesssim \mathbb{S}}{\Gamma \vdash A \times B \lesssim \mathbb{S}} S_ProdSL \quad \frac{\Gamma \vdash A \lesssim \mathbb{S} \quad \Gamma \vdash B \lesssim \mathbb{S}}{\Gamma \vdash A \rightarrow B \lesssim \mathbb{S}} S_ArrowSL \\
 \\
 \frac{\Gamma \vdash A \lesssim B}{\Gamma \vdash (\text{List } A) \lesssim (\text{List } B)} \text{List} \quad \frac{\Gamma \vdash A_1 \lesssim A_2 \quad \Gamma \vdash B_1 \lesssim B_2}{\Gamma \vdash (A_1 \times B_1) \lesssim (A_2 \times B_2)} \times \\
 \\
 \frac{\Gamma \vdash A_2 \lesssim A_1 \quad \Gamma \vdash B_1 \lesssim B_2}{\Gamma \vdash (A_1 \rightarrow B_1) \lesssim (A_2 \rightarrow B_2)} \rightarrow \quad \frac{\Gamma, X <: A \vdash B_1 \lesssim B_2}{\Gamma \vdash (\forall(X <: A).B_1) \lesssim (\forall(X <: A).B_2)} \forall
 \end{array}$$

Fig. 5. Subtyping for Surface Grady

$$\begin{array}{c}
 \frac{\Gamma \vdash A : \star}{\Gamma \vdash A \sim A} \text{refl} \quad \frac{\Gamma \vdash A \lesssim \mathbb{S}}{\Gamma \vdash A \sim ?} \text{box} \quad \frac{\Gamma \vdash A \lesssim \mathbb{S}}{\Gamma \vdash ? \sim A} \text{unbox} \\
 \\
 \frac{\Gamma \vdash A \sim B}{\Gamma \vdash (\text{List } A) \sim (\text{List } B)} \text{List} \quad \frac{\Gamma \vdash A_2 \sim A_1 \quad \Gamma \vdash B_1 \sim B_2}{\Gamma \vdash (A_1 \rightarrow B_1) \sim (A_2 \rightarrow B_2)} \rightarrow \\
 \\
 \frac{\Gamma \vdash A_1 \sim A_2 \quad \Gamma \vdash B_1 \sim B_2}{\Gamma \vdash (A_1 \times B_1) \sim (A_2 \times B_2)} \times \quad \frac{\Gamma, X <: A \vdash B_1 \sim B_2}{\Gamma \vdash (\forall(X <: A).B_1) \sim (\forall(X <: A).B_2)} \forall
 \end{array}$$

Fig. 6. Type consistency for Surface Grady

- Scott Encoded data, this is not available in terminating type theories
- Parigot Encoded Data, better efficiency

$\frac{x : A \in \Gamma \quad \Gamma \text{ Ok}}{\Gamma \vdash_{\text{SG}} x : A} \text{ var}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{SG}} \text{box} : \forall (X <: \mathbb{S}). (X \rightarrow ?)} \text{ box}$
$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{SG}} \text{unbox} : \forall (X <: \mathbb{S}). (? \rightarrow X)} \text{ unbox}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{SG}} \text{triv} : \text{Unit}} \text{ Unit}$
$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{SG}} 0 : \text{Nat}} \text{ zero}$	$\frac{\Gamma \vdash_{\text{SG}} t : A \quad \text{nat}(A) = \text{Nat}}{\Gamma \vdash_{\text{SG}} \text{succ } t : \text{Nat}} \text{ succ}$
$\frac{\Gamma \vdash_{\text{SG}} t : C \quad \text{nat}(C) = \text{Nat} \quad \Gamma \vdash A_1 \sim A \quad \Gamma \vdash_{\text{SG}} t_1 : A_1 \quad \Gamma, x : \text{Nat} \vdash_{\text{SG}} t_2 : A_2 \quad \Gamma \vdash A_2 \sim A}{\Gamma \vdash_{\text{SG}} \text{case } t \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 : A} \text{ Nat}_e$	
$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{SG}} [] : \forall (X <: \mathbb{T}). \text{List } X} \text{ empty}$	
$\frac{\Gamma \vdash_{\text{SG}} t_1 : A_1 \quad \Gamma \vdash_{\text{SG}} t_2 : A_2 \quad \text{list}(A_2) = \text{List } A_3 \quad \Gamma \vdash A_1 \sim A_3}{\Gamma \vdash_{\text{SG}} t_1 :: t_2 : \text{List } A_3} \text{ List}_i$	
$\Gamma \vdash_{\text{SG}} t : C \quad \text{list}(C) = \text{List } A$	
$\frac{\Gamma \vdash_{\text{SG}} t_1 : B_1 \quad \Gamma, x : A, y : \text{List } A \vdash_{\text{SG}} t_2 : B_2 \quad \Gamma \vdash B_1 \sim B \quad \Gamma \vdash B_2 \sim B}{\Gamma \vdash_{\text{SG}} \text{case } t \text{ of } [] \rightarrow t_1, (x :: y) \rightarrow t_2 : B} \text{ List}_e$	
$\frac{\Gamma \vdash_{\text{SG}} t_1 : A_1 \quad \Gamma \vdash_{\text{SG}} t_2 : A_2}{\Gamma \vdash_{\text{SG}} (t_1, t_2) : A_1 \times A_2} \times_i$	$\frac{\Gamma \vdash_{\text{SG}} t : B \quad \text{prod}(B) = A_1 \times A_2}{\Gamma \vdash_{\text{SG}} \text{fst } t : A_1} \times_{e1}$
$\frac{\Gamma \vdash_{\text{SG}} t : B \quad \text{prod}(B) = A_1 \times A_2}{\Gamma \vdash_{\text{SG}} \text{snd } t : A_2} \times_{e2}$	$\frac{\Gamma, x : A \vdash_{\text{SG}} t : B}{\Gamma \vdash_{\text{SG}} \lambda(x : A). t : A \rightarrow B} \rightarrow_i$
$\Gamma \vdash_{\text{SG}} t_1 : C \quad \text{fun}(C) = A_1 \rightarrow B_1$	
$\frac{\Gamma \vdash_{\text{SG}} t_2 : A_2 \quad \Gamma \vdash A_2 \sim A_1}{\Gamma \vdash_{\text{SG}} t_1 t_2 : B_1} \rightarrow_e$	$\frac{\Gamma, X <: A \vdash_{\text{SG}} t : B}{\Gamma \vdash_{\text{SG}} \Lambda(X <: A). t : \forall (X <: A). B} \forall_i$
$\frac{\Gamma \vdash_{\text{SG}} t : \forall (X <: B). C \quad \Gamma \vdash A \lesssim B}{\Gamma \vdash_{\text{SG}} [A]t : [A/X]C} \forall_e$	$\frac{\Gamma \vdash_{\text{SG}} t : A \quad \Gamma \vdash A \lesssim B}{\Gamma \vdash_{\text{SG}} t : B} \text{ sub}$

Fig. 7. Typing rules for Surface Grady

$\frac{x : A \in \Gamma \quad \Gamma \text{ Ok}}{\Gamma \vdash x \Rightarrow x : A}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash \text{box} \Rightarrow \text{box} : \forall (X <: \mathbb{S}). (X \rightarrow ?)}$
$\frac{\Gamma \text{ Ok}}{\Gamma \vdash \text{unbox} \Rightarrow \text{unbox} : \forall (X <: \mathbb{S}). (? \rightarrow X)}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash 0 \Rightarrow 0 : \text{Nat}}$
$\frac{\Gamma \text{ Ok}}{\Gamma \vdash \text{triv} \Rightarrow \text{triv} : \text{Unit}}$	$\frac{\Gamma \vdash t_1 \Rightarrow t_2 : ?}{\Gamma \vdash \text{succ } t_1 \Rightarrow \text{succ } (\text{unbox}_{\text{Nat}} t_2) : \text{Nat}}$
$\frac{\Gamma \vdash t_1 \Rightarrow t_2 : \text{Nat}}{\Gamma \vdash \text{succ } t_1 \Rightarrow \text{succ } t_2 : \text{Nat}}$	
$\frac{\Gamma \vdash t \Rightarrow t' : ? \quad \Gamma \vdash A_1 \sim A \quad \text{caster}(A_1, A) = c_1 \quad \Gamma \vdash t_1 \Rightarrow t'_1 : A_1 \quad \Gamma, x : \text{Nat} \vdash t_2 \Rightarrow t'_2 : A_2 \quad \Gamma \vdash A_2 \sim A \quad \text{caster}(A_2, A) = c_2}{\Gamma \vdash (\text{case } t \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2) \Rightarrow (\text{case } (\text{unbox}_{\text{Nat}} t') \text{ of } 0 \rightarrow (c_1 t'_1), (\text{succ } x) \rightarrow (c_2 t'_2)) : A}$	
$\frac{\Gamma \vdash t \Rightarrow t' : \text{Nat} \quad \Gamma \vdash A_1 \sim A \quad \text{caster}(A_1, A) = c_1 \quad \Gamma \vdash t_1 \Rightarrow t'_1 : A_1 \quad \Gamma, x : \text{Nat} \vdash t_2 \Rightarrow t'_2 : A_2 \quad \Gamma \vdash A_2 \sim A \quad \text{caster}(A_2, A) = c_2}{\Gamma \vdash (\text{case } t \text{ of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2) \Rightarrow (\text{case } t' \text{ of } 0 \rightarrow t'_1, (\text{succ } x) \rightarrow t'_2) : A}$	
$\frac{\Gamma \vdash t_1 \Rightarrow t_3 : A_1 \quad \Gamma \vdash t_2 \Rightarrow t_4 : A_2}{\Gamma \vdash (t_1, t_2) \Rightarrow (t_3, t_4) : A_1 \times A_2}$	$\frac{\Gamma \vdash t_1 \Rightarrow t_2 : ?}{\Gamma \vdash \text{fst } t_1 \Rightarrow \text{fst } (\text{split}_{(? \times ?)} t_2) : ?}$
$\frac{\Gamma \vdash t_1 \Rightarrow t_2 : A_1 \times A_2}{\Gamma \vdash \text{fst } t_1 \Rightarrow \text{fst } t_2 : A_1}$	$\frac{\Gamma \vdash t_1 \Rightarrow t_2 : ?}{\Gamma \vdash \text{snd } t_1 \Rightarrow \text{snd } (\text{split}_{(? \times ?)} t_2) : ?}$
$\frac{\Gamma \vdash t_1 \Rightarrow t_2 : A \times B}{\Gamma \vdash \text{snd } t_1 \Rightarrow \text{snd } t_2 : B}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash [] \Rightarrow [] : \forall (X <: \mathbb{T}). \text{List } X}$
$\frac{\Gamma \vdash t_1 \Rightarrow t'_1 : A_1 \quad \Gamma \vdash t_2 \Rightarrow t'_2 : \text{List } A_2 \quad \Gamma \vdash A_1 \lesssim A_2 \quad \text{caster}(A_1, A_2) = c}{\Gamma \vdash (t_1 :: t_2) \Rightarrow ((c t'_1) :: t'_2) : \text{List } A_2}$	
$\frac{\Gamma \vdash t \Rightarrow t' : ? \quad \text{caster}(B_1, B) = c_1 \quad \text{caster}(B_2, B) = c_2 \quad \Gamma \vdash t_1 \Rightarrow t'_1 : B_1 \quad \Gamma, x : ?, y : \text{List } ? \vdash t_2 \Rightarrow t'_2 : B_2 \quad \Gamma \vdash B_1 \sim B \quad \Gamma \vdash B_2 \sim B}{\Gamma \vdash (\text{case } t \text{ of } [] \rightarrow t_1, (x :: y) \rightarrow t_2) \Rightarrow (\text{case } (\text{split}_{(\text{List } ?)} t') \text{ of } [] \rightarrow (c_1 t'_1), (x :: y) \rightarrow (c_2 t'_2)) : B}$	
$\frac{\Gamma \vdash t \Rightarrow t : \text{List } A \quad \text{caster}(B_1, B) = c_1 \quad \text{caster}(B_2, B) = c_2 \quad \Gamma \vdash t_1 \Rightarrow t'_1 : B_1 \quad \Gamma, x : A, y : \text{List } A \vdash t_2 \Rightarrow t'_2 : B_2 \quad \Gamma \vdash B_1 \sim B \quad \Gamma \vdash B_2 \sim B}{\Gamma \vdash (\text{case } t \text{ of } [] \rightarrow t_1, (x :: y) \rightarrow t_2) \Rightarrow (\text{case } t' \text{ of } [] \rightarrow (c_1 t'_1), (x :: y) \rightarrow (c_2 t'_2)) : B}$	
$\frac{\Gamma, x : A_1 \vdash t_1 \Rightarrow t_2 : A_2}{\Gamma \vdash \lambda(x : A_1). t_1 \Rightarrow \lambda(x : A_1). t_2 : A_1 \rightarrow A_2}$	

TODO

Fig. 9. Subtyping for Core Grady

5 Grady: A Categorically Inspired Gradual Type System

5.1 Surface Grady: A Gradual Type System

5.2 Core Grady: The Casting Calculus

5.3 Analyzing Grady

Lemma 5.1 (Inclusion of Bounded System F) *Suppose t is fully annotated and does not contain any applications of `box` or `unbox`, and A is static. Then*

- i. $\Gamma \vdash_F t : A$ if and only if $\Gamma \vdash_{\text{SG}} t : A$, and
- ii. $t \rightsquigarrow_F^* t'$ if and only if $t \rightsquigarrow^* t'$.

Proof. We give proof sketches for both parts. The interesting cases are the right-to-left directions of each part. If we simply remove all rules mentioning the unknown type $?$ and the type consistency relation, and then remove `box`, `unbox`, and $?$ from the syntax of Surface Grady, then what we are left with is bounded system F. Since t is fully annotated and A is static, then $\Gamma \vdash_{\text{SG}} t : A$ will hold within this fragment.

Moving on to part two, first, we know that t does not contain any occurrence of `box` or `unbox` and is fully annotated. This implies that t lives within the bounded system F fragment of Surface Grady. Thus, before evaluation of t Surface Grady will apply the cast insertion algorithm which will at most insert applications of the identity function into t producing a term \hat{t} , but then after potentially more than one step of evaluation within Core Grady, those applications of the identity function will be β -reduced away resulting in $\hat{t} \rightsquigarrow^* t \rightsquigarrow^* t'$. In addition, since t in Surface Grady is the exact same program as t in bounded system F, then we know $t \rightsquigarrow_F^* t'$ will hold. \square

Lemma 5.2 (Inclusion of DTLC) *Suppose t is a closed term of DTLC. Then*

- i. $\cdot \vdash_{\text{SG}} [t] : ?$, and
- ii. $t \rightsquigarrow_{\text{DTLC}}^* t'$ if and only if $[t] \rightsquigarrow^* [t']$.

Proof. In this case DTLC is embedded into the simply typed fragment of Grady, and hence, this proof is the same result proven by [8], and [9]. \square

Lemma 5.3 (Left-to-Right Consistent Subtyping) *Suppose $\Gamma \vdash A \lesssim B$.*

- i. $\Gamma \vdash A \sim A'$ and $\Gamma \vdash A' <: B$ for some A' .
- ii. $\Gamma \vdash B' \sim B$ and $\Gamma \vdash A <: B'$ for some B' .

Proof. This is a proof by induction on $\Gamma \vdash A \lesssim B$. See Appendix B.7 for the complete proof. \square

$\frac{x : A \in \Gamma \quad \Gamma \text{ Ok}}{\Gamma \vdash_{\text{CG}} x : A} \text{ var}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{CG}} \text{box} : \forall (X <: \mathbb{S}). (X \rightarrow ?)} \text{ box}$	
$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{CG}} \text{unbox} : \forall (X <: \mathbb{S}). (? \rightarrow X)} \text{ unbox}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{CG}} \text{squash}_K : K \rightarrow ?} \text{ squash}$	
$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{CG}} \text{split}_K : ? \rightarrow K} \text{ split}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{CG}} \text{triv} : \text{Unit}} \text{ Unit}$	$\frac{\Gamma \text{ Ok}}{\Gamma \vdash_{\text{CG}} 0 : \text{Nat}} \text{ zero}$
$\frac{\Gamma \vdash_{\text{CG}} t : \text{Nat}}{\Gamma \vdash_{\text{CG}} \text{succ } t : \text{Nat}} \text{ succ}$	$\frac{\Gamma \vdash_{\text{CG}} t_1 : A \quad \Gamma, x : \text{Nat} \vdash_{\text{CG}} t_2 : A}{\Gamma \vdash_{\text{CG}} \text{case } t : \text{Nat of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 : A} \text{ Nat}_e$	
$\frac{\Gamma \text{ Ok} \quad \Gamma \vdash A : \star}{\Gamma \vdash_{\text{CG}} [] : \forall (X <: ?). \text{List } X} \text{ empty}$	$\frac{\Gamma \vdash_{\text{CG}} t_1 : A \quad \Gamma \vdash_{\text{CG}} t_2 : \text{List } A}{\Gamma \vdash_{\text{CG}} t_1 :: t_2 : \text{List } A} \text{ List}_i$	
$\frac{\Gamma \vdash_{\text{CG}} t : \text{List } A \quad \Gamma \vdash_{\text{CG}} t_1 : B \quad \Gamma, x : A, y : \text{List } A \vdash_{\text{CG}} t_2 : B}{\Gamma \vdash_{\text{CG}} \text{case } t : \text{List } A \text{ of } [] \rightarrow t_1, (x :: y) \rightarrow t_2 : B} \text{ List}_e$		
$\frac{\Gamma \vdash_{\text{CG}} t_1 : A_1 \quad \Gamma \vdash_{\text{CG}} t_2 : A_2}{\Gamma \vdash_{\text{CG}} (t_1, t_2) : A_1 \times A_2} \times_i$	$\frac{\Gamma \vdash_{\text{CG}} t : A_1 \times A_2}{\Gamma \vdash_{\text{CG}} \text{fst } t : A_1} \times_{e1}$	
$\frac{\Gamma \vdash_{\text{CG}} t : A_1 \times A_2}{\Gamma \vdash_{\text{CG}} \text{snd } t : A_2} \times_{e2}$	$\frac{\Gamma, x : A \vdash_{\text{CG}} t : B}{\Gamma \vdash_{\text{CG}} \lambda(x : A). t : A \rightarrow B} \rightarrow_i$	
$\frac{\Gamma \vdash_{\text{CG}} t_1 : A \rightarrow B \quad \Gamma \vdash_{\text{CG}} t_2 : A}{\Gamma \vdash_{\text{CG}} t_1 t_2 : B} \rightarrow_e$	$\frac{\Gamma, X <: A \vdash_{\text{CG}} t : B}{\Gamma \vdash_{\text{CG}} \Lambda(X <: A). t : \forall (X <: A). B} \forall_i$	
$\frac{\Gamma \vdash_{\text{CG}} t : \forall (X <: B). C \quad \Gamma \vdash A <: B}{\Gamma \vdash_{\text{CG}} [A]t : [A/X]C} \forall_e$	$\frac{\Gamma \vdash_{\text{CG}} t : A \quad \Gamma \vdash A <: B}{\Gamma \vdash_{\text{CG}} t : B} \text{ sub}$	
$\frac{}{\Gamma \vdash_{\text{CG}} \text{error}_A : A} \text{ error}$		

Fig. 10. Typing rules for Core Grady

TODO

Fig. 11. Reduction rules for Core Grady

$$\begin{array}{c}
 \frac{\Gamma \vdash A \lesssim \mathbb{S}}{A \sqsubseteq ?} ? \qquad \frac{}{A \sqsubseteq A} \text{refl} \qquad \frac{A \sqsubseteq C \quad B \sqsubseteq D}{(A \rightarrow B) \sqsubseteq (C \rightarrow D)} \rightarrow \\
 \\
 \frac{A \sqsubseteq C \quad B \sqsubseteq D}{(A \times B) \sqsubseteq (C \times D)} \times \qquad \frac{A \sqsubseteq B}{(\text{List } A) \sqsubseteq (\text{List } B)} \text{List} \\
 \\
 \frac{B_1 \sqsubseteq B_2}{(\forall (X <: A). B_1) \sqsubseteq (\forall (X <: A). B_2)} \forall
 \end{array}$$

Fig. 12. Type Precision

Corollary 5.4 (Consistent Subtyping)

- i. $\Gamma \vdash A \lesssim B$ if and only if $\Gamma \vdash A \sim A'$ and $\Gamma \vdash A' <: B$ for some A' .
- ii. $\Gamma \vdash A \lesssim B$ if and only if $\Gamma \vdash B' \sim B$ and $\Gamma \vdash A <: B'$ for some B' .

Proof. The left-to-right direction of both cases easily follows from Lemma 5.3, and the right-to-left direction of both cases follows from induction on the subtyping derivation and Lemma A.20. \square

Lemma 5.5 (Gradual Guarantee Part One) *If $\Gamma \vdash_{\text{SG}} t : A$, $t \sqsubseteq t'$, and $\Gamma \sqsubseteq \Gamma'$ then $\Gamma' \vdash_{\text{SG}} t' : B$ and $A \sqsubseteq B$.*

Proof. This is a proof by induction on $\Gamma \vdash_{\text{SG}} t : A$; see Appendix B.10 for the complete proof. \square

Lemma 5.6 (Type Preservation for Cast Insertion) *If $\Gamma \vdash_{\text{SG}} t_1 : A$ and $\Gamma \vdash t_1 \Rightarrow t_2 : B$, then $\Gamma \vdash_{\text{CG}} t_2 : B$ and $\Gamma \vdash A \sim B$.*

Proof. The cast insertion algorithm is type directed and with respect to every term t_1 it will produce a term t_2 of the core language with the type A – this is straightforward to show by induction on the form of $\Gamma \vdash_{\text{SG}} t_1 : A$ making use of typing for casting morphisms Lemma A.26 – except in the case of type application. Please see Appendix B.11 for the complete proof. \square

Lemma 5.7 (Type Preservation) *If $\Gamma \vdash_{\text{CG}} t_1 : A$ and $t_1 \rightsquigarrow t_2$, then $\Gamma \vdash_{\text{CG}} t_2 : A$.*

Proof. This proof holds by induction on $\Gamma \vdash_{\text{CG}} t_1 : A$ with further case analysis on the structure the derivation $t_1 \rightsquigarrow t_2$. \square

Lemma 5.8 (Simulation of More Precise Programs) *Suppose $\Gamma \vdash_{\text{CG}} t_1 : A$, $\Gamma \vdash t_1 \sqsubseteq t'_1$, $\Gamma \vdash_{\text{CG}} t'_1 : A'$, and $t_1 \rightsquigarrow t_2$. Then $t'_1 \rightsquigarrow^* t'_2$ and $\Gamma \vdash t_2 \sqsubseteq t'_2$ for some t'_2 .*

Proof. This proof holds by induction on $\Gamma \vdash_{\text{CG}} t_1 : A_1$. See Appendix B.12 for the complete proof. \square

Theorem 5.9 (Gradual Guarantee)

- i. If $\cdot \vdash_{\text{SG}} t : A$ and $t \sqsubseteq t'$, then $\cdot \vdash_{\text{SG}} t' : B$ and $A \sqsubseteq B$.
- ii. Suppose $\cdot \vdash_{\text{CG}} t : A$ and $\cdot \vdash t \sqsubseteq t'$. Then
 - a. if $t \rightsquigarrow^* v$, then $t' \rightsquigarrow^* v'$ and $\cdot \vdash v \sqsubseteq v'$,
 - b. if $t \uparrow$, then $t' \uparrow$,
 - c. if $t' \rightsquigarrow^* v'$, then $t \rightsquigarrow^* v$ where $\cdot \vdash v \sqsubseteq v'$, or $t \rightsquigarrow^* \text{error}_A$, and
 - d. if $t' \uparrow$, then $t \uparrow$ or $t \rightsquigarrow^* \text{error}_A$.

Proof. This result follows from the same proof as [9], and so, we only give a brief summary. Part i. holds by Lemma 5.5, and Part ii. follows from simulation of more precise programs (Lemma 5.8). \square

References

- [1] Abadi, M., L. Cardelli, B. Pierce and G. Plotkin, *Dynamic typing in a statically-typed language*, in: *Proceedings of the 16th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, POPL '89 (1989), pp. 213–227.
- [2] Crole, R. L., “Categories for Types,” Cambridge University Press, 1994.
- [3] Garcia, R., A. M. Clark and E. Tanter, *Abstracting gradual typing*, in: *Proceedings of the 43rd Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, POPL '16 (2016), pp. 429–442.
- [4] Henglein, F., *Dynamic typing: syntax and proof theory*, Science of Computer Programming **22** (1994), pp. 197 – 230.
- [5] Lambek, J., *From lambda calculus to cartesian closed categories*, To H. B. Curry: Essays on Combinatory Logic, Lambda Calculus and Formalism (1980), pp. 376–402.
- [6] Lambek, J. and P. Scott, “Introduction to Higher-Order Categorical Logic,” Cambridge Studies in Advanced Mathematics, Cambridge University Press, 1988.
- [7] Scott, D., *Relating theories of the lambda-calculus*, in: *To H.B. Curry: Essays on Combinatory Logic, Lambda-Calculus and Formalism* (eds. Hindley and Seldin) (1980), pp. 403–450.
- [8] Siek, J. G. and W. Taha, *Gradual typing for functional languages*, in: *Scheme and Functional Programming Workshop*, 1 **6**, 2006, pp. 81–92.
- [9] Siek, J. G., M. M. Vitousek, M. Cimini and J. T. Boyland, *Refined Criteria for Gradual Typing*, in: T. Ball, R. Bodik, S. Krishnamurthi, B. S. Lerner and G. Morrisett, editors, *1st Summit on Advances in Programming Languages (SNAPL 2015)*, Leibniz International Proceedings in Informatics (LIPIcs) **32** (2015), pp. 274–293.

A Auxiliary Results with Proofs

Lemma A.1 (Kinding)

- i. If $\Gamma \vdash A \sim B$, then $\Gamma \vdash A : \star$ and $\Gamma \vdash B : \star$.
- ii. If $\Gamma \vdash A \lesssim B$, then $\Gamma \vdash A : \star$ and $\Gamma \vdash B : \star$.
- iii. If $\Gamma \vdash_{\text{SG}} t : A$, then $\Gamma \vdash A : \star$.

Proof. This proof holds by straightforward induction the form of each assumed judgment. \square

Lemma A.2 (Strengthening for Kinding) If $\Gamma, x : A \vdash B : \star$, then $\Gamma \vdash B : \star$.

Proof. This proof holds by straightforward induction on the form of $\Gamma, x : A \vdash B : \star$. \square

Lemma A.3 (Inversion for Type Precision) *Suppose $\Gamma \vdash A : \star$, $\Gamma \vdash B : \star$, and $A \sqsubseteq B$. Then:*

- i. if $A = ?$, then $\Gamma \vdash B \lesssim \mathbb{S}$.
- ii. if $A = A_1 \rightarrow B_1$, then $B = ?$ and $\Gamma \vdash A \lesssim \mathbb{S}$, or $B = A_2 \rightarrow B_2$, $A_1 \sqsubseteq A_2$, and $B_1 \sqsubseteq B_2$.
- iii. if $A = A_1 \times B_1$, then $B = ?$ and $\Gamma \vdash A \lesssim \mathbb{S}$, or $B = A_2 \times B_2$, $A_1 \sqsubseteq A_2$, and $B_1 \sqsubseteq B_2$.
- iv. if $A = \text{List } A_1$, then $B = ?$ and $\Gamma \vdash A \lesssim \mathbb{S}$, or $B = \text{List } A_2$ and $A_1 \sqsubseteq A_2$.
- v. if $A = \forall(X <: A_1).B_1$, then $B = \forall(X <: A_1).B_1$ and $B_1 \sqsubseteq B_2$.

Proof. This proof holds by straightforward induction on the form of $A \sqsubseteq B$. \square

Lemma A.4 (Surface Grady Inversion for Term Precision) *Suppose $t \sqsubseteq t'$. Then:*

- i. if $t = \text{succ } t_1$, then $t' = \text{succ } t_2$ and $t_1 \sqsubseteq t_2$.
- ii. if $t = (\text{case } t_1 \text{ of } 0 \rightarrow t_2, (\text{succ } x) \rightarrow t_3)$, then $t' = (\text{case } t'_1 \text{ of } 0 \rightarrow t'_2, (\text{succ } x) \rightarrow t'_3)$, $t_1 \sqsubseteq t'_1$, $t_2 \sqsubseteq t'_2$, and $t_3 \sqsubseteq t'_3$.
- iii. if $t = (t_1, t_2)$, then $t' = (t'_1, t'_2)$, $t_1 \sqsubseteq t'_1$, and $t_2 \sqsubseteq t'_2$.
- iv. if $t = \text{fst } t_1$, then $t' = \text{fst } t'_1$ and $t_1 \sqsubseteq t'_1$.
- v. if $t = \text{snd } t_1$, then $t' = \text{snd } t'_1$ and $t_1 \sqsubseteq t'_1$.
- vi. if $t = t_1 :: t_2$, then $t' = t'_1 :: t'_2$, $t_1 \sqsubseteq t'_1$, and $t_2 \sqsubseteq t'_2$.
- vii. if $t = (\text{case } t_1 \text{ of } [] \rightarrow t_2, (x :: y) \rightarrow t_3)$, then $t' = (\text{case } t'_1 \text{ of } [] \rightarrow t'_2, (x :: y) \rightarrow t'_3)$, $t_1 \sqsubseteq t'_1$, $t_2 \sqsubseteq t'_2$, and $t_3 \sqsubseteq t'_3$.
- viii. if $t = \lambda(x : A_1).t_1$, then $t' = \lambda(x : A_1).t'_1$ and $t_1 \sqsubseteq t'_1$.
- ix. if $t = (t_1 t_2)$, then $t' = (t'_1 t'_2)$, $t_1 \sqsubseteq t'_1$, and $t_2 \sqsubseteq t'_2$.
- x. if $t = \Lambda(X <: A_1).t_1$, then $t' = \Lambda(X <: A_1).t'_1$ and $t_1 \sqsubseteq t'_1$.
- xi. if $t = [A]t_1$, then $t' = [A]t'_1$ and $t_1 \sqsubseteq t'_1$.

Proof. This proof holds by straightforward induction on the form of $t \sqsubseteq t'$. \square

Lemma A.5 (Inversion for Type Consistency) *Suppose $\Gamma \vdash A \sim B$. Then:*

- i. if $A = ?$, then $\Gamma \vdash B \lesssim \mathbb{S}$.
- ii. if $A = \text{List } A'$, then $B = ?$ and $\Gamma \vdash A \lesssim \mathbb{S}$, or $B = \text{List } B'$ and $\Gamma \vdash A' \sim B'$.
- iii. if $A = A_1 \rightarrow B_1$, then $B = ?$ and $\Gamma \vdash A \lesssim \mathbb{S}$, or $B = A_2 \rightarrow B_2$, $\Gamma \vdash A_2 \sim A_1$, and $\Gamma \vdash B_1 \sim B_2$.
- iv. if $A = A_1 \times B_1$, then $B = ?$ and $\Gamma \vdash A \lesssim \mathbb{S}$, or $B = A_2 \times B_2$, $\Gamma \vdash A_1 \sim A_2$, and $\Gamma \vdash B_1 \sim B_2$.
- v. if $A = \forall(X <: A_1).B_1$, then $B = \forall(X <: A_1).B_2$ and $\Gamma, X <: A_1 \vdash B_1 \sim B_2$.

Proof. This proof holds by straightforward induction on the the form of $\Gamma \vdash A \sim B$. \square

Lemma A.6 (Inversion for Consistent Subtyping) *Suppose $\Gamma \vdash A \lesssim B$. Then:*

- i. *if $A = ?$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ or $\Gamma \vdash B \lesssim \mathbb{S}$.*
- ii. *if $A = X$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ and $\Gamma \vdash A : \star$, or $X <: B' \in \Gamma$ and $\Gamma \vdash B' \sim B$.*
- iii. *if $A = \text{Nat}$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ and $\Gamma \vdash A : \star$, or $B = \mathbb{S}$.*
- iv. *if $A = \text{Unit}$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ and $\Gamma \vdash A : \star$, or $B = \mathbb{S}$.*
- v. *if $A = \text{List } A_1$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ and $\Gamma \vdash A : \star$, $B = \mathbb{S}$ and $\Gamma \vdash A_1 \lesssim \mathbb{S}$, or $B = \text{List } A'_1$ and $\Gamma \vdash A_1 \lesssim A'_1$.*
- vi. *if $A = A_1 \rightarrow B_1$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ and $\Gamma \vdash A : \star$, $B = \mathbb{S}$, $\Gamma \vdash A_1 \lesssim \mathbb{S}$ and $\Gamma \vdash B_1 \lesssim \mathbb{S}$, or $B = A'_1 \rightarrow B'_1$, $\Gamma \vdash A'_1 \lesssim A_1$, and $\Gamma \vdash B_1 \lesssim B'_1$.*
- vii. *if $A = A_1 \times B_1$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ and $\Gamma \vdash A : \star$, $B = \mathbb{S}$, $\Gamma \vdash A_1 \lesssim \mathbb{S}$ and $\Gamma \vdash B_1 \lesssim \mathbb{S}$, or $B = A'_1 \times B'_1$, $\Gamma \vdash A_1 \lesssim A'_1$, and $\Gamma \vdash B_1 \lesssim B'_1$.*
- viii. *if $A = \forall(X <: A_1).B_1$, then $B = A$ and $\Gamma \vdash A : \star$, $B = \top$ and $\Gamma \vdash A : \star$, or $B = \forall(X <: A_1).B'_1$ and $\Gamma, X <: A_1 \vdash B_1 \lesssim B'_1$.*

Proof. This proof holds by straightforward induction on the the form of $\Gamma \vdash A \lesssim B$. \square

Lemma A.7 (Symmetry for Type Consistency) *If $\Gamma \vdash A \sim B$, then $\Gamma \vdash B \sim A$.*

Proof. This holds by straightforward induction on the form of $\Gamma \vdash A \sim B$. \square

Lemma A.8 *If $\Gamma \vdash A <: B$, then $\Gamma \vdash A \lesssim B$.*

Proof. This proof holds by straightforward induction on $\Gamma \vdash A <: B$. \square

Lemma A.9 *if $\Gamma \vdash A \sim B$, then $\Gamma \vdash A \lesssim B$.*

Proof. By straightforward induction on $\Gamma \vdash A \sim B$. \square

Lemma A.10 (Type Precision and Consistency) *Suppose $\Gamma \vdash A : \star$ and $\Gamma \vdash B : \star$. Then if $A \sqsubseteq B$, then $\Gamma \vdash A \sim B$.*

Proof. This proof holds by straightforward induction on $A \sqsubseteq B$. \square

Corollary A.11 (Type Precision and Subtyping) *Suppose $\Gamma \vdash A : \star$ and $\Gamma \vdash B : \star$. Then if $A \sqsubseteq B$, then $\Gamma \vdash A \lesssim B$.*

Proof. This easily follows from the previous two lemmas. \square

Lemma A.12 *Suppose $\Gamma \vdash A : \star$, $\Gamma \vdash B : \star$, and $\Gamma \vdash C : \star$. If $A \sqsubseteq B$ and $A \sqsubseteq C$, then $\Gamma \vdash B \sim C$.*

Proof. It must be the case that either $B \sqsubseteq C$ or $C \sqsubseteq B$, but in both cases we know $\Gamma \vdash B \sim C$ by Lemma A.10. \square

Lemma A.13 (Transitivity for Type Precision) *If $A \sqsubseteq B$ and $B \sqsubseteq C$, then $A \sqsubseteq C$.*

Proof. This proof holds by straightforward induction on $A \sqsubseteq B$ with a case analysis over $B \sqsubseteq C$. \square

Lemma A.14 *If $\Gamma \vdash A \sim B$, then $A \sqsubseteq B$ or $B \sqsubseteq A$.*

Proof. This proof holds by straightforward induction over $\Gamma \vdash A \sim B$. \square

Lemma A.15 *If $\Gamma \vdash A \lesssim B$ and $A \sqsubseteq A'$, then $B \sqsubseteq A'$ or $A' \sqsubseteq B$.*

Proof. Suppose $\Gamma \vdash A \lesssim B$ and $A \sqsubseteq A'$. The former implies that $A \sqsubseteq B$ or $B \sqsubseteq A$ by Lemma 5.3 and Lemma A.14. At this point the result easily follows. \square

Lemma A.16 *Suppose $A \sqsubseteq B$. Then*

- i. *If $\text{nat}(A) = \text{Nat}$, then $\text{nat}(B) = \text{Nat}$.*
- ii. *If $\text{list}(A) = \text{List } C$, then $\text{list}(B) = \text{List } C'$ and $C \sqsubseteq C'$.*
- iii. *If $\text{fun}(A) = A_1 \rightarrow A_2$, then $\text{fun}(B) = A'_1 \rightarrow A'_2$, $A_1 \sqsubseteq A'_1$, and $A_2 \sqsubseteq A'_2$.*

Proof. This proof holds by straightforward induction on $A \sqsubseteq B$. \square

Lemma A.17 *If $\Gamma \vdash A \sim B$, $\Gamma \vdash C : \star$, and $A \sqsubseteq C$, then $\Gamma \vdash C \sim B$.*

Proof. Suppose $\Gamma \vdash A \sim B$ and $A \sqsubseteq C$. Then we know that $A \sqsubseteq B$ or $B \sqsubseteq A$. If the former, then we know that $\Gamma \vdash C \sim B$. If the latter, then we obtain $B \sqsubseteq C$ by transitivity, and $\Gamma \vdash B \sim C$ which implies that $\Gamma \vdash C \sim B$ by symmetry. \square

Lemma A.18 *If Γ' Ok, $\Gamma \sqsubseteq \Gamma'$ and $\Gamma \vdash A \sim B$, then $\Gamma' \vdash A \sim B$.*

Proof. This proof holds by straightforward induction on $\Gamma \vdash A \sim B$. \square

Lemma A.19 (Subtyping Context Precision) *If $\Gamma \vdash A \lesssim B$ and $\Gamma \sqsubseteq \Gamma'$, then $\Gamma' \vdash A \lesssim B$.*

Proof. Context precision does not manipulate the bounds on type variables, and thus, with respect to subtyping Γ and Γ' are essentially equivalent. \square

Lemma A.20 (Simply Typed Consistent Types are Subtypes of \mathbb{S}) *If $\Gamma \vdash A \lesssim \mathbb{S}$ and $\Gamma \vdash A \sim B$, then $\Gamma \vdash B \lesssim \mathbb{S}$.*

Proof. This holds by straightforward induction on the form of $\Gamma \vdash A \lesssim \mathbb{S}$. \square

Lemma A.21 (Type Precision Preserves \mathbb{S})

- i. *If $\Gamma \vdash B : \star$, $\Gamma \vdash A \lesssim \mathbb{S}$ and $A \sqsubseteq B$, then $\Gamma \vdash B \lesssim \mathbb{S}$.*
- ii. *If $\Gamma \vdash A : \star$, $\Gamma \vdash B \lesssim \mathbb{S}$ and $A \sqsubseteq B$, then $\Gamma \vdash A \lesssim \mathbb{S}$.*

Proof. Both cases follow by induction on the assumed consistent subtyping derivation. \square

Lemma A.22 (Congruence of Type Consistency Along Type Precision)

- i. *If $A_1 \sqsubseteq A'_1$ and $\Gamma \vdash A_1 \sim A_2$ then $\Gamma \vdash A'_1 \sim A_2$.*
- ii. *If $A_2 \sqsubseteq A'_2$ and $\Gamma \vdash A_1 \sim A_2$ then $\Gamma \vdash A_1 \sim A'_2$.*

Proof. Both parts hold by induction on the assumed type consistency judgment. See Appendix B.8 for the complete proof. \square

Corollary A.23 (Congruence of Type Consistency Along Type Precision Condensed) *If $A_1 \sqsubseteq A'_1$, $A_2 \sqsubseteq A'_2$, and $\Gamma \vdash A_1 \sim A_2$ then $\Gamma \vdash A'_1 \sim A'_2$.*

Lemma A.24 (Congruence of Subtyping Along Type Precision) *Suppose $\Gamma \vdash B : \star$ and $A \sqsubseteq B$.*

- i. *If $\Gamma \vdash A \lesssim C$ then $\Gamma \vdash B \lesssim C$.*
- ii. *If $\Gamma \vdash C \lesssim A$ then $\Gamma \vdash C \lesssim B$.*

Proof. This is a proof by induction on the form of $A \sqsubseteq B$; see Appendix B.9 for the complete proof. \square

Corollary A.25 (Congruence of Subtyping Along Type Precision) *If $A_1 \sqsubseteq A_2$, $B_1 \sqsubseteq B_2$, and $\Gamma \vdash A_1 \lesssim B_1$, then $\Gamma \vdash A_2 \lesssim B_2$.*

Lemma A.26 (Typing Casting Morphisms) *If $\Gamma \vdash A \sim B$ and $\text{caster}(A, B) = c$, then $\Gamma \vdash_{\text{CG}} c : A \rightarrow B$.*

Proof. This proof holds similarly to how we constructed casting morphisms in the categorical model. See Lemma 3.11. \square

Lemma A.27 (Substitution for Consistent Subtyping) *If $\Gamma, X <: B_1 \vdash B_2 \lesssim B_3$ and $\Gamma \vdash A_1 \lesssim B_1$, then $\Gamma \vdash [A_1/X]B_2 \lesssim [A_1/X]B_3$.*

Proof. This holds by straightforward induction on the form of $\Gamma, X <: B_1 \vdash B_2 \lesssim B_3$. \square

Lemma A.28 (Substitution for Reflexive Type Consistency) *If $\Gamma, X <: B_1 \vdash B \sim B$, $\Gamma \vdash A_1 \sim A_2$, and $\Gamma \vdash A_2 <: B_1$, then $\Gamma \vdash [A_1/X]B \sim [A_2/X]B$.*

Proof. This holds by straightforward induction on the form of B . \square

Lemma A.29 (Substitution for Type Consistency) *If $\Gamma, X <: B_1 \vdash B_2 \sim B_3$, $\Gamma \vdash A_1 \sim A_2$, and $\Gamma \vdash A_1 <: B_1$, then $\Gamma \vdash [A_1/X]B_2 \sim [A_2/X]B_3$.*

Proof. This holds by straightforward induction on $\Gamma, X <: B_1 \vdash B_2 \sim B_3$ using both substitution for consistent subtyping (Lemma A.27) and substitution for reflexive type consistent (Lemma A.28). \square

Lemma A.30 (Typing for Type Precision) *If $\Gamma \vdash_{\text{SG}} t_1 : A$, $t_1 \sqsubseteq t_2$, and $\Gamma \sqsubseteq \Gamma'$, then $\Gamma' \vdash_{\text{SG}} t_2 : B$ and $A \sqsubseteq B$.*

Proof. This proof holds by induction on $\Gamma \vdash_{\text{SG}} t_1 : A$ with a case analysis over $t_1 \sqsubseteq t_2$. \square

Lemma A.31 (Substitution for Term Precision)

- i. *If $\Gamma, x : A \vdash t_1 \sqsubseteq t_2$ and $\Gamma \vdash t'_1 \sqsubseteq t'_2$, then $\Gamma \vdash [t'_1/x]t_1 \sqsubseteq [t'_2/x]t_2$.*
- ii. *If $\Gamma, X <: A_2 \vdash t_1 \sqsubseteq t_2$ and $A_1 \sqsubseteq A'_1$, then $\Gamma \vdash [A_1/X]t_1 \sqsubseteq [A'_1/X]t_2$.*

Proof. This proof of part one holds by straightforward induction on $\Gamma, x : A \vdash t_1 \sqsubseteq t_2$, and the proof of part two holds by straightforward induction on $\Gamma, X <: A_2 \vdash t_1 \sqsubseteq t_2$. \square

Lemma A.32 (Typeability Inversion)

- i. If $\Gamma \vdash_{\text{CG}} \text{succ } t : A$, then $\Gamma \vdash_{\text{CG}} t : A'$ for some A' .
- ii. If $\Gamma \vdash_{\text{CG}} \text{case } t : \text{Nat of } 0 \rightarrow t_1, (\text{succ } x) \rightarrow t_2 : A$, then $\Gamma \vdash_{\text{CG}} t : A_1$, $\Gamma \vdash_{\text{CG}} t_1 : A_2$, and $\Gamma, x : \text{Nat} \vdash_{\text{CG}} t_2 : A_3$ for types A_1, A_2, A_3 .
- iii. If $\Gamma \vdash_{\text{CG}} (t_1, t_2) : A$, then $\Gamma \vdash_{\text{CG}} t_1 : A_1$ and $\Gamma \vdash_{\text{CG}} t_2 : A_2$ for types A_1 and A_2 .
- iv. If $\Gamma \vdash_{\text{CG}} \Lambda(X <: B).t : A$, then $\Gamma, X <: B \vdash_{\text{CG}} t : A_1$ for some type A_1 .
- v. If $\Gamma \vdash_{\text{CG}} [B]t : A$, then $\Gamma \vdash_{\text{CG}} t : A_1$ for some type A_1 .
- vi. If $\Gamma \vdash_{\text{CG}} \lambda(x : B).t : A$, then $\Gamma, x : B \vdash_{\text{CG}} t : A_1$ for some type A_1 .
- vii. If $\Gamma \vdash_{\text{CG}} t_1 t_2 : A$, then $\Gamma \vdash_{\text{CG}} t_1 : A_1$ and $\Gamma \vdash_{\text{CG}} t_2 : A_2$ for types A_1 and A_2 .
- viii. If $\Gamma \vdash_{\text{CG}} \text{fst } t : A$, then $\Gamma \vdash_{\text{CG}} t : A_1$ for some type A_1 .
- ix. If $\Gamma \vdash_{\text{CG}} \text{snd } t : A$, then $\Gamma \vdash_{\text{CG}} t : A_1$ for some type A_1 .
- x. If $\Gamma \vdash_{\text{CG}} t_1 :: t_2 : A$, then $\Gamma \vdash_{\text{CG}} t_1 : A_1$ and $\Gamma \vdash_{\text{CG}} t_2 : A_2$ for some types A_1 and A_2 .
- xi. If $\Gamma \vdash_{\text{CG}} \text{case } t : \text{List } B \text{ of } [] \rightarrow t_1, (x :: y) \rightarrow t_2 : A$, then $\Gamma \vdash_{\text{CG}} t : A_1$, $\Gamma \vdash_{\text{CG}} t_1 : A_2$, and $\Gamma, x : A, y : \text{List } A \vdash_{\text{CG}} t_2 : A_3$ for types A_1, A_2, A_3 .

Lemma A.33 (Inversion for Term Precision for Core Grady) Suppose $\Gamma \vdash t_1 \sqsubseteq t_2$.

- i. If $t_1 = x$, then one of the following is true:
 - a. $t_2 = x$, $x : A \in \Gamma$, and $\Gamma \text{ Ok}$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- ii. If $t_1 = \text{split}_{K_1}$, then one of the following is true:
 - a. $t_2 = \text{split}_{K_2}$ and $K_1 \sqsubseteq K_2$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- iii. If $t_1 = \text{squash}_{K_1}$, then one of the following is true:
 - a. $t_2 = \text{squash}_{K_2}$ and $K_1 \sqsubseteq K_2$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- iv. If $t_1 = \text{box}$, then one of the following is true:
 - a. $t_2 = \text{box}$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- v. If $t_1 = \text{unbox}$, then one of the following is true:
 - a. $t_2 = \text{unbox}$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$

- vi. *If $t_1 = 0$, then one of the following is true:*
 - a. $t_2 = 0$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- vii. *If $t_1 = \text{triv}$, then one of the following is true:*
 - a. $t_2 = \text{triv}$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- viii. *If $t_1 = []$, then one of the following is true:*
 - a. $t_2 = []$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- ix. *If $t_1 = \text{succ } t'_1$, then one of the following is true:*
 - a. $t_2 = \text{succ } t'_2$ and $\Gamma \vdash t'_1 \sqsubseteq t'_2$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- x. *If $t_1 = \text{case } t'_1 : \text{Nat of } 0 \rightarrow t'_2, (\text{succ } x) \rightarrow t'_3$, then one of the following is true:*
 - a. $t_2 = \text{case } t'_4 : \text{Nat of } 0 \rightarrow t'_5, (\text{succ } x) \rightarrow t'_6$, $\Gamma \vdash t'_1 \sqsubseteq t'_4$, $\Gamma \vdash t'_2 \sqsubseteq t'_5$, and $\Gamma, x : \text{Nat} \vdash t'_3 \sqsubseteq t'_6$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- xi. *If $t_1 = (t'_1, t'_2)$, then one of the following is true:*
 - a. $t_2 = (t'_3, t'_4)$, $\Gamma \vdash t'_1 \sqsubseteq t'_3$, and $\Gamma \vdash t'_2 \sqsubseteq t'_4$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- xii. *If $t_1 = \text{fst } t'_1$, then one of the following is true:*
 - a. $t_2 = \text{fst } t'_2$ and $\Gamma \vdash t'_1 \sqsubseteq t'_2$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- xiii. *If $t_1 = \text{snd } t'_1$, then one of the following is true:*
 - a. $t_2 = \text{snd } t'_2$ and $\Gamma \vdash t'_1 \sqsubseteq t'_2$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- xiv. *If $t_1 = t'_1 :: t'_2$, then one of the following is true:*
 - a. $t_2 = t'_3 :: t'_4$, $\Gamma \vdash t'_1 \sqsubseteq t'_3$, and $\Gamma \vdash t'_2 \sqsubseteq t'_4$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- xv. *If $t_1 = \text{case } t'_1 : \text{List } A_1 \text{ of } [] \rightarrow t'_2, (x :: y) \rightarrow t'_3$, then one of the following is true:*
 - a. $t_2 = \text{case } t'_4 : \text{List } A_2 \text{ of } [] \rightarrow t'_5, (x :: y) \rightarrow t'_6$, $\Gamma \vdash t'_1 \sqsubseteq t'_4$, $\Gamma \vdash t'_2 \sqsubseteq t'_5$, and $\Gamma, x : A_2, y : \text{List } A_2 \vdash t'_3 \sqsubseteq t'_6$, and $A_1 \sqsubseteq A_2$
 - b. $t_2 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
 - c. $t_2 = \text{squash}_K t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K$
- xvi. *If $t_1 = \lambda(x : A_1).t_1$, then one of the following is true:*
 - a. $t_2 = \lambda(x : A_2).t_2$ and $\Gamma, x : A_2 \vdash t_1 \sqsubseteq t_2$ and $A_1 \sqsubseteq A_2$

- b. $t_2 = \mathbf{box}_A t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : A$
- c. $t_2 = \mathbf{squash}_K t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : K$
- xvii. If $t_1 = t'_1 t'_2$, then one of the following is true:
 - a. $t_2 = t'_3 t'_4$, $\Gamma \vdash t_3 \sqsubseteq t'_3$, and $\Gamma \vdash t_4 \sqsubseteq t'_4$
 - b. $t'_1 = \mathbf{unbox}_A$ and $t_2 = t'_2$
 - c. $t'_1 = \mathbf{split}_K$ and $t_2 = t'_2$
 - d. $t_2 = \mathbf{box}_A t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : A$
 - e. $t_2 = \mathbf{squash}_K t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : K$
- xviii. If $t_1 = \mathbf{unbox}_A t'_1$, then one of the following is true:
 - a. $t_2 = t'_1$ and $\Gamma \vdash_{\mathbf{CG}} t'_1 : ?$
 - b. $t_2 = \mathbf{box}_A t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : A$
 - c. $t_2 = \mathbf{squash}_K t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : K$
- xix. If $t_1 = \mathbf{split}_K t'_1$, then one of the following is true:
 - a. $t_2 = t'_1$ and $\Gamma \vdash_{\mathbf{CG}} t'_1 : K$
 - b. $t_2 = \mathbf{box}_A t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : A$
 - c. $t_2 = \mathbf{squash}_K t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : K$
- xx. If $t_1 = \Lambda(X <: A).t'_1$, then one of the following is true:
 - a. $t_2 = \Lambda(X <: A).t'_2$ and $\Gamma, X <: A_2 \vdash t'_1 \sqsubseteq t'_2$
 - b. $t_2 = \mathbf{box}_A t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : A$
 - c. $t_2 = \mathbf{squash}_K t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : K$
- xxi. If $t_1 = [A_1]t'_1$, then one of the following is true:
 - a. $t_2 = [A_2]t'_2$, $\Gamma \vdash t'_1 \sqsubseteq t'_2$, and $A_1 \sqsubseteq A_2$
 - b. $t_2 = \mathbf{box}_A t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : A$
 - c. $t_2 = \mathbf{squash}_K t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : K$
- xxii. If $t_1 = \mathbf{error}_{A_1}$, then one of the following is true:
 - a. $\Gamma \vdash_{\mathbf{CG}} t_2 : A_2$ and $A_1 \sqsubseteq A_2$
 - b. $t_2 = \mathbf{box}_A t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : A$
 - c. $t_2 = \mathbf{squash}_K t_1$ and $\Gamma \vdash_{\mathbf{CG}} t_1 : K$

Proof. The proof of this result holds by straightforward induction on $\Gamma \vdash t_1 \sqsubseteq t_2$. \square

B Proofs

B.1 Proof of Lifted Retract (Lemma 3.6)

This is a proof by induction on the form of A .

Case. Suppose A is atomic. Then:

$$\widehat{\mathbf{box}_A}; \widehat{\mathbf{unbox}_A} = \mathbf{box}_A; \mathbf{unbox}_A = \mathbf{id}_A$$

Case. Suppose A is $?$. Then:

$$\begin{aligned}\widehat{\text{box}}_A; \widehat{\text{unbox}}_A &= \widehat{\text{box}}_?; \widehat{\text{unbox}}_? \\ &= \text{id}_?; \text{id}_? \\ &= \text{id}_? \\ &= \text{id}_A\end{aligned}$$

Case. Suppose $A = A_1 \rightarrow A_2$. Then:

$$\begin{aligned}\widehat{\text{box}}_A; \widehat{\text{unbox}}_A &= \widehat{\text{box}}_{(A_1 \rightarrow A_2)}; \widehat{\text{unbox}}_{(A_1 \rightarrow A_2)} \\ &= (\widehat{\text{unbox}}_{A_1} \rightarrow \widehat{\text{box}}_{A_2}); (\widehat{\text{box}}_{A_1} \rightarrow \widehat{\text{box}}_{A_2}) \\ &= (\widehat{\text{box}}_{A_1}; \widehat{\text{unbox}}_{A_1}) \rightarrow (\widehat{\text{box}}_{A_2}; \widehat{\text{unbox}}_{A_2})\end{aligned}$$

By two applications of the induction hypothesis we know the following:

$$\widehat{\text{box}}_{A_1}; \widehat{\text{unbox}}_{A_1} = \text{id}_{A_1} \quad \text{and} \quad \widehat{\text{box}}_{A_2}; \widehat{\text{unbox}}_{A_2} = \text{id}_{A_2}$$

Thus, we know the following:

$$\begin{aligned}(\widehat{\text{box}}_{A_1}; \widehat{\text{unbox}}_{A_1}) \rightarrow (\widehat{\text{box}}_{A_2}; \widehat{\text{unbox}}_{A_2}) &= \text{id}_{A_1} \rightarrow \text{id}_{A_2} \\ &= \text{id}_{A_1 \rightarrow A_2} \\ &= \text{id}_A\end{aligned}$$

Case. Suppose $A = A_1 \times A_2$. Then:

$$\begin{aligned}\widehat{\text{box}}_A; \widehat{\text{unbox}}_A &= \widehat{\text{box}}_{(A_1 \times A_2)}; \widehat{\text{unbox}}_{(A_1 \times A_2)} \\ &= (\widehat{\text{box}}_{A_1} \times \widehat{\text{box}}_{A_2}); (\widehat{\text{unbox}}_{A_1} \times \widehat{\text{box}}_{A_2}) \\ &= (\widehat{\text{box}}_{A_1}; \widehat{\text{unbox}}_{A_1}) \times (\widehat{\text{box}}_{A_2}; \widehat{\text{unbox}}_{A_2})\end{aligned}$$

By two applications of the induction hypothesis we know the following:

$$\widehat{\text{box}}_{A_1}; \widehat{\text{unbox}}_{A_1} = \text{id}_{A_1} \quad \text{and} \quad \widehat{\text{box}}_{A_2}; \widehat{\text{unbox}}_{A_2} = \text{id}_{A_2}$$

Thus, we know the following:

$$\begin{aligned}(\widehat{\text{box}}_{A_1}; \widehat{\text{unbox}}_{A_1}) \times (\widehat{\text{box}}_{A_2}; \widehat{\text{unbox}}_{A_2}) &= \text{id}_{A_1} \times \text{id}_{A_2} \\ &= \text{id}_{A_1 \times A_2} \\ &= \text{id}_A\end{aligned}$$

B.2 Proof of Lemma 3.7

We must show that the function

$$S_{A,B} : \text{Hom}_{\mathcal{C}}(A, B) \longrightarrow \text{Hom}_{\mathcal{S}}(SA, SB)$$

is injective.

So suppose $f \in \text{Hom}_C(A, B)$ and $g \in \text{Hom}_C(A, B)$ such that $Sf = Sg : SA \rightarrow SB$. Then we can easily see that:

$$\begin{aligned} Sf &= \widehat{\text{unbox}_A}; f; \widehat{\text{box}_B} \\ &= \widehat{\text{unbox}_A}; g; \widehat{\text{box}_B} \\ &= Sg \end{aligned}$$

But, we have the following equalities:

$$\begin{aligned} \widehat{\text{unbox}_A}; f; \widehat{\text{box}_B} &= \widehat{\text{unbox}_A}; g; \widehat{\text{box}_B} \\ \widehat{\text{box}_A}; \widehat{\text{unbox}_A}; f; \widehat{\text{box}_B}; \widehat{\text{unbox}_B} &= \widehat{\text{box}_A}; \widehat{\text{unbox}_A}; g; \widehat{\text{box}_B}; \widehat{\text{unbox}_B} \\ \text{id}_A; f; \widehat{\text{box}_B}; \widehat{\text{unbox}_B} &= \text{id}_A; g; \widehat{\text{box}_B}; \widehat{\text{unbox}_B} \\ \text{id}_A; f; \text{id}_B &= \text{id}_A; g; \text{id}_B \\ f &= g \end{aligned}$$

The previous equalities hold due to Lemma 3.6.

B.3 Proof of Type Consistency in the Model (Lemma 3.13)

This is a proof by induction on the form of $A \sim B$.

Case.

$$\frac{}{A \sim A} \text{ refl}$$

Choose $c_1 = c_2 = \text{id}_A : A \rightarrow A$.

Case.

$$\frac{}{A \sim ?} \text{ box}$$

Choose $c_1 = \text{Box}_A : A \rightarrow ?$ and $c_2 = \text{Unbox}_A : ? \rightarrow A$.

Case.

$$\frac{}{? \sim A} \text{ unbox}$$

Choose $c_1 = \text{Unbox}_A : ? \rightarrow A$ and $c_2 = \text{Box}_A : A \rightarrow ?$.

Case.

$$\frac{A_1 \sim A_2 \quad B_1 \sim B_2}{A_1 \rightarrow B_1 \sim A_2 \rightarrow B_2} \rightarrow$$

By the induction hypothesis there exists four casting morphisms $c'_1 : A_1 \rightarrow A_2$, $c'_2 : A_2 \rightarrow A_1$, $c'_3 : B_1 \rightarrow B_2$, and $c'_4 : B_2 \rightarrow B_1$. Choose $c_1 = c'_2 \rightarrow c'_3 : (A_1 \rightarrow B_1) \rightarrow (A_2 \rightarrow B_2)$ and $c_2 = c'_1 \rightarrow c'_4 : (A_2 \rightarrow B_2) \rightarrow (A_1 \rightarrow B_1)$.

Case.

$$\frac{A_1 \sim A_2 \quad B_1 \sim B_2}{A_1 \times B_1 \sim A_2 \times B_2} \times$$

By the induction hypothesis there exists four casting morphisms $c'_1 : A_1 \rightarrow A_2$, $c'_2 : A_2 \rightarrow A_1$, $c'_3 : B_1 \rightarrow B_2$, and $c'_4 : B_2 \rightarrow B_1$. Choose $c_1 = c'_1 \times c'_3 : A_1 \times B_1 \rightarrow A_2 \times B_2$ and $c_2 = c'_2 \times c'_4 : A_2 \times B_2 \rightarrow A_1 \times B_1$.

B.4 Proof of Interpretation of Types Theorem 3.15

First, we show how to interpret the rules of $\lambda_{\rightarrow}^?$, and then $\lambda_{\rightarrow}^{\Rightarrow}$. This is a proof by induction on $\Gamma \vdash_{\mathcal{S}} t : A$.

Case.

$$\frac{x : A \in \Gamma}{\Gamma \vdash_{\mathcal{S}} x : A} \text{var}$$

Suppose with out loss of generality that $\llbracket \Gamma \rrbracket = A_1 \times \cdots \times A_i \times \cdots \times A_j$ where $A_i = A$. We know that $j > 0$ or the assumed typing derivation would not hold. Then take $\llbracket x \rrbracket = \pi_i : \llbracket \Gamma \rrbracket \rightarrow A$.

Case.

$$\frac{}{\Gamma \vdash_{\mathcal{S}} \text{triv} : \text{Unit}} \text{unit}$$

Take $\llbracket \text{triv} \rrbracket = \diamond_{\llbracket \Gamma \rrbracket} : \llbracket \Gamma \rrbracket \rightarrow 1$ where $\diamond_{\llbracket \Gamma \rrbracket}$ is the unique terminal arrow that exists because \mathcal{C} is cartesian closed.

Case.

$$\frac{}{\Gamma \vdash_{\mathcal{S}} 0 : \text{Nat}} \text{zero}$$

Take $\llbracket 0 \rrbracket = \diamond_{\llbracket \Gamma \rrbracket}; z : \llbracket \Gamma \rrbracket \rightarrow \text{Nat}$ where $z : 1 \rightarrow \text{Nat}$ exists because \mathcal{C} has a SNNO.

Case.

$$\frac{\Gamma \vdash_{\mathcal{S}} t : A \quad \text{nat}(A) = \text{Nat}}{\Gamma \vdash_{\mathcal{S}} \text{succ } t : \text{Nat}} \text{succ}$$

First, by the induction hypothesis there is a morphism $\llbracket t \rrbracket : \llbracket \Gamma \rrbracket \rightarrow A$. Now we have two cases to consider, one when $A = ?$ and one when $A = \text{Nat}$. Consider the former. Then interpret $\llbracket \text{succ } t \rrbracket = \llbracket t \rrbracket; \text{unbox}_{\text{Nat}}; \text{succ} : \llbracket \Gamma \rrbracket \rightarrow \text{Nat}$ where $\text{succ} : \text{Nat} \rightarrow \text{Nat}$ exists because \mathcal{C} has a SNNO. Similarly, when $A = \text{Nat}$, $\llbracket \text{succ } t \rrbracket = \llbracket t \rrbracket; \text{succ} : \llbracket \Gamma \rrbracket \rightarrow \text{Nat}$.

Case.

$$\frac{\Gamma \vdash_{\mathcal{S}} t_1 : A_1 \quad \Gamma \vdash_{\mathcal{S}} t_2 : A_2}{\Gamma \vdash_{\mathcal{S}} (t_1, t_2) : A_1 \times A_2} \times$$

By two applications of the induction hypothesis there are two morphisms $\llbracket t_1 \rrbracket : \llbracket \Gamma \rrbracket \rightarrow A$ and $\llbracket t_2 \rrbracket : \llbracket \Gamma \rrbracket \rightarrow B$. Then using the fact that \mathcal{C} is cartesian we take $\llbracket (t_1, t_2) \rrbracket = \langle \llbracket t_1 \rrbracket, \llbracket t_2 \rrbracket \rangle : \llbracket \Gamma \rrbracket \rightarrow A \times B$.

Case.

$$\frac{\Gamma \vdash_{\mathcal{S}} t : B \quad \text{prod}(B) = A_1 \times A_2}{\Gamma \vdash_{\mathcal{S}} \text{fst } t : A_1} \times_{e_1}$$

First, by the induction hypothesis there is a morphism $\llbracket t \rrbracket : \llbracket \Gamma \rrbracket \rightarrow B$. Now we have two cases to consider, one when $B = ?$ and one when $B = A_1 \times A_2$ for some types A_1 and A_2 . Consider the former. We then know that it must be the case that $A_1 \times A_2 = ? \times ?$. Thus, we obtain the following interpretation $\llbracket \text{fst } t \rrbracket = \llbracket t \rrbracket; \text{split}_{(? \times ?)}; \pi_1 : \llbracket \Gamma \rrbracket \rightarrow ?$. Similarly, when $B = A_1 \times A_2$, then $\llbracket \text{fst } t \rrbracket = \llbracket t \rrbracket; \pi_1 : \llbracket \Gamma \rrbracket \rightarrow A_1$.

Case.

$$\frac{\Gamma \vdash_S t : B \quad \text{prod}(B) = A_1 \times A_2}{\Gamma \vdash_S \text{snd } t : A_2} \times_{e_2}$$

First, by the induction hypothesis there is a morphism $\llbracket t \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow B$. Now we have two cases to consider, one when $B = ?$ and one when $B = A_1 \times A_2$ for some types A_1 and A_2 . Consider the former. We then know that it must be the case that $A_1 \times A_2 = ? \times ?$. Thus, we obtain the following interpretation $\llbracket \text{snd } t \rrbracket = \llbracket t \rrbracket; \text{split}_{(? \times ?)}; \pi_2 : \llbracket \Gamma \rrbracket \longrightarrow ?$. Similarly, when $B = A_1 \times A_2$, then $\llbracket \text{snd } t \rrbracket = \llbracket t \rrbracket; \pi_2 : \llbracket \Gamma \rrbracket \longrightarrow A_2$.

Case.

$$\frac{\Gamma, x : A \vdash_S t : B}{\Gamma \vdash_S \lambda x : A. t : A \rightarrow B} \rightarrow$$

By the induction hypothesis there is a morphism $\llbracket t \rrbracket : \llbracket \Gamma \rrbracket \times A \longrightarrow B$. Then take $\llbracket \lambda x : A. t \rrbracket = \text{curry}(\llbracket t \rrbracket) : \llbracket \Gamma \rrbracket \longrightarrow (A \rightarrow B)$, where $\text{curry} : \text{Hom}_{\mathcal{C}}(X \times Y, Z) \longrightarrow \text{Hom}_{\mathcal{C}}(X, Y \rightarrow Z)$ exists because \mathcal{C} is closed.

Case.

$$\frac{\Gamma \vdash_S t_1 : C \quad \Gamma \vdash_S t_2 : A_2 \quad A_2 \sim A_1 \quad \text{fun}(C) = A_1 \rightarrow B_1}{\Gamma \vdash_S t_1 t_2 : B_1} \rightarrow_e$$

By the induction hypothesis there are two morphisms $\llbracket t_1 \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow C$ and $\llbracket t_2 \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow A_2$. In addition, by assumption we know that $A_2 \sim A_1$, and hence, by type consistency in the model (Lemma 3.13) there are casting morphisms $c_1 : A_2 \longrightarrow A_1$ and $c_2 : A_1 \longrightarrow A_2$. We have two cases to consider, one when $C = ?$ and one when $C = A_1 \rightarrow B_1$. Consider the former. Then we have the interpretation

$$\llbracket t_1 t_2 \rrbracket = \langle \llbracket t_1 \rrbracket; \text{split}_{(? \rightarrow ?)}, \llbracket t_2 \rrbracket; c_1 \rangle; \text{app}_{A_2, B_1} : \llbracket \Gamma \rrbracket \longrightarrow B_1.$$

Similarly, for the case when $C = A_1 \rightarrow B_1$ we have the interpretation

$$\llbracket t_1 t_2 \rrbracket = \langle \llbracket t_1 \rrbracket, \llbracket t_2 \rrbracket; c_1 \rangle; \text{app}_{A_1, B_1} : \llbracket \Gamma \rrbracket \longrightarrow B_1.$$

Note that $\text{app}_{A_1, B_1} : (A_1 \rightarrow B_1) \times A_1 \longrightarrow B_1$ exists because the model is cartesian closed.

Next we turn to $\lambda \overrightarrow{x}. t$, but we do not show every rule, because it corresponds to the simply typed λ -calculus whose interpretation is similar to what we have already shown above except without casting morphism, and so we only show the case for the cast rule.

Case.

$$\frac{\Gamma \vdash_C t : A \quad A \sim B}{\Gamma \vdash_C (t : A \Rightarrow B) : B} \text{cast}$$

By the induction hypothesis there is a morphism $\llbracket t \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow A$, and by type consistency in the model (Lemma 3.13) there is a casting morphism $c_1 : A \longrightarrow B$. So take $\llbracket t : A \Rightarrow B \rrbracket = \llbracket t \rrbracket; c_1 : \llbracket \Gamma \rrbracket \longrightarrow B$.

B.5 Proof of Interpretation of Evaluation (Theorem 3.16)

This proof holds by induction on the form of $\Gamma \vdash t_1 \rightsquigarrow t_2 : A$. We only show the cases for the casting rules, because the others are well-known to hold within any cartesian closed category; see [5] or [2]. We will routinely use Theorem 3.15 throughout this proof without mention.

Case.

$$\frac{\Gamma \vdash_{\mathbf{C}} v : T}{\Gamma \vdash v : T \Rightarrow T \rightsquigarrow v : T} \text{ID-ATOM}$$

We have a morphism $\llbracket v : T \Rightarrow T \rrbracket = \llbracket v \rrbracket; c_1 : \llbracket \Gamma \rrbracket \longrightarrow T$ based on the interpretation of typing where $c_1 : T \longrightarrow T$, but it must be the case that $c_1 = \text{id}_T : T \longrightarrow T$ by Corollary 3.14. Thus, $\llbracket v : T \Rightarrow T \rrbracket = \llbracket v \rrbracket; c_1 = \llbracket v \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow T$.

Case.

$$\frac{\Gamma \vdash_{\mathbf{C}} v : ?}{\Gamma \vdash v : ? \Rightarrow ? \rightsquigarrow v : ?} \text{ID-U}$$

Similar to the previous case.

Case.

$$\frac{\Gamma \vdash_{\mathbf{C}} v : R}{\Gamma \vdash v : R \Rightarrow ? \Rightarrow R \rightsquigarrow v : R} \text{SUCCEED}$$

The typing derivation for $v : R \Rightarrow ? \Rightarrow R$ is as follows:

$$\frac{\frac{\Gamma \vdash_{\mathbf{C}} v : R \quad R \sim ?}{\Gamma \vdash_{\mathbf{C}} v : R \Rightarrow ? : ?} \quad ? \sim R}{\Gamma \vdash_{\mathbf{C}} v : R \Rightarrow ? \Rightarrow R : R}$$

By the induction hypothesis we have the morphism $\llbracket v \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow R$. As we can see we will first use Box_R and then Unbox_R based on Corollary 3.14. Thus, $\llbracket v : R \Rightarrow ? \Rightarrow R \rrbracket = \llbracket v \rrbracket; \text{Box}_R; \text{Unbox}_R = \llbracket v \rrbracket$, because Box_R and Unbox_R form a retract.

Case.

$$\frac{\Gamma \vdash_{\mathbf{C}} v_1 : A_1 \rightarrow B_1 \quad \Gamma \vdash_{\mathbf{C}} v_2 : A_2 \quad (A_1 \rightarrow B_1) \sim (A_2 \rightarrow B_2)}{\Gamma \vdash (v_1 : (A_1 \rightarrow B_1) \Rightarrow (A_2 \rightarrow B_2)) v_2 \rightsquigarrow v_1 (v_2 : A_2 \Rightarrow A_1) : B_1 \Rightarrow B_2 : B_2} \text{ARROW}$$

By the induction hypothesis and Corollary 3.14 we have the following mor-

phisms:

$$\begin{aligned} \llbracket v_1 \rrbracket : \llbracket \Gamma \rrbracket &\longrightarrow (A_1 \rightarrow B_1) \\ \llbracket v_2 \rrbracket : \llbracket \Gamma \rrbracket &\longrightarrow A_2 \\ c_1 : A_2 &\longrightarrow A_1 \\ c_2 : B_1 &\longrightarrow B_2 \end{aligned}$$

We must show the following:

$$\begin{aligned} \llbracket (v_1 : (A_1 \rightarrow B_1) \Rightarrow (A_2 \rightarrow B_2)) v_2 \rrbracket &= \langle \llbracket v_1 \rrbracket; (c_1 \rightarrow c_2), \llbracket v_2 \rrbracket \rangle; \mathbf{app}_{A_2, B_2} \\ &= \langle \llbracket v_1 \rrbracket, \llbracket v_2 \rrbracket; c_1 \rangle; \mathbf{app}_{A_1, B_1}; c_2 \end{aligned}$$

The previous equation holds as follows:

$$\begin{aligned} &\langle \llbracket v_1 \rrbracket, \llbracket v_2 \rrbracket; c_1 \rangle; \mathbf{app}_{A_1, B_1}; c_2 \\ &= \langle \llbracket v_1 \rrbracket, \llbracket v_2 \rrbracket \rangle; (\mathbf{id}_{A_1 \rightarrow B_1} \times c_1); \mathbf{app}_{A_1, B_1}; c_2 && \text{(Cartesian Products)} \\ &= \langle \llbracket v_1 \rrbracket, \llbracket v_2 \rrbracket \rangle; (\mathbf{id}_{A_1 \rightarrow B_1} \times c_1); ((\mathbf{id}_{A_1} \rightarrow c_2) \times \mathbf{id}_{A_1}); \mathbf{app}_{A_1, B_2} && \text{(Naturality)} \\ &= \langle \llbracket v_1 \rrbracket, \llbracket v_2 \rrbracket \rangle; (\mathbf{curry}((\mathbf{id}_{A_1 \rightarrow B_1} \times c_1); ((\mathbf{id}_{A_1} \rightarrow c_2) \times \mathbf{id}_{A_1})); \mathbf{app}_{A_1, B_2}) \times \mathbf{id}_{A_2}; \mathbf{app}_{A_2, B_2} && \text{(Closure)} \\ &= \langle \llbracket v_1 \rrbracket, \llbracket v_2 \rrbracket \rangle; ((c_1 \rightarrow c_2) \times \mathbf{id}_{A_2}); \mathbf{app}_{A_2, B_2} && \text{(Closure)} \\ &= \langle \llbracket v_1 \rrbracket; (c_1 \rightarrow c_2), \llbracket v_2 \rrbracket; \mathbf{id}_{A_2} \rangle; \mathbf{app}_{A_2, B_2} && \text{(Cartesian)} \\ &= \langle \llbracket v_1 \rrbracket; (c_1 \rightarrow c_2), \llbracket v_2 \rrbracket \rangle; \mathbf{app}_{A_2, B_2} \end{aligned}$$

Case.

$$\frac{\Gamma \vdash_{\mathbf{C}} v : A \quad A \sim R \quad A \neq R \quad A \neq ?}{\Gamma \vdash v : A \Rightarrow ? \rightsquigarrow v : A \Rightarrow R \Rightarrow ? : ?} \text{EXPAND}_1$$

By the induction hypothesis and Lemma 3.13 we have the following morphisms:

$$\begin{aligned} \llbracket v \rrbracket : \llbracket \Gamma \rrbracket &\longrightarrow A \\ c_1 : A &\longrightarrow R \end{aligned}$$

We must show the following:

$$\begin{aligned} \llbracket v : A \Rightarrow ? \rrbracket &= \llbracket v \rrbracket; \mathbf{Box}_A \\ &= \llbracket v \rrbracket; c_1; \mathbf{Box}_R \end{aligned}$$

However, notice that given the constraints above, it must be the case that $R = T$ or $R = ? \rightarrow ?$. If the former is true, then $A = T$ by the definition of consistency and the constraints above, but this implies that $c_1 = \mathbf{id}_T$ by Corollary 3.14, and the result follows. However, consider the case when $R = ? \rightarrow ?$. Then given the constraints above $A = A_1 \rightarrow A_2$. Thus, $c_1 = (\mathbf{unbox}_{A_1} \rightarrow \mathbf{box}_{A_2})$ by Corollary 3.14. In addition, it must be the case that $\mathbf{Box}_R = \mathbf{squash}_{(? \rightarrow ?)}$ by the definition of \mathbf{Box}_R , but by inspection of the

definition of \mathbf{Box}_A we have the following:

$$\begin{aligned}
 \mathbf{Box}_A &= \mathbf{Box}_{(A_1 \rightarrow A_2)} \\
 &= (\mathbf{unbox}_{A_1} \rightarrow \mathbf{box}_{A_2}); \mathbf{squash}_{(? \rightarrow ?)} \\
 &= c_1; \mathbf{squash}_{(? \rightarrow ?)} \\
 &= c_1; \mathbf{Box}_R
 \end{aligned}$$

Thus, we obtain our result.

Case.

$$\frac{\Gamma \vdash_{\mathbf{C}} v : ? \quad A \sim R \quad A \neq R \quad A \neq ?}{\Gamma \vdash v : ? \Rightarrow A \rightsquigarrow v : ? \Rightarrow R \Rightarrow A : A} \text{EXPAND}_2$$

This case is similar to the previous case, except that the interpretation uses \mathbf{Unbox}_A and \mathbf{Unbox}_R instead of \mathbf{Box}_A and \mathbf{Box}_R .

B.6 Proof of Lemma 4.2

First, we define the identify meta-function:

$$\mathbf{id}_A := \lambda x : A. x$$

Then composition. Suppose $\Gamma \vdash t_1 : A \rightarrow B$ and $\Gamma \vdash t_2 : B \rightarrow D$ are two terms, then we define:

$$t_1; t_2 := \lambda x : A. t_2(t_1 x)$$

It is easy to see that the following rule is admissible:

$$\frac{\Gamma \vdash t_1 : A \rightarrow B \quad \Gamma \vdash t_2 : B \rightarrow D}{\Gamma \vdash t_1; t_2 : A \rightarrow D} \text{COMP}$$

The functor $- \times -$ requires two morphisms $\Gamma \vdash t_1 : A \rightarrow D$ and $\Gamma \vdash t_2 : B \rightarrow E$, and is defined as follows:

$$t_1 \times t_2 := \lambda x : A \times B. (t_1(\mathbf{fst } x), t_2(\mathbf{snd } x))$$

The following rule is admissible:

$$\frac{\Gamma \vdash t_1 : A \rightarrow D \quad \Gamma \vdash t_2 : B \rightarrow E}{\Gamma \vdash t_1 \times t_2 : A \times B \rightarrow D \times E} \text{PROD}$$

The functor $- \rightarrow -$ requires two morphisms $\Gamma \vdash t_1 : D \rightarrow A$ and $\Gamma \vdash t_2 : B \rightarrow E$, and is defined as follows:

$$t_1 \rightarrow t_2 := \lambda f : A \rightarrow B. \lambda y : D. t_2(f(t_1 y))$$

The following rule is admissible:

$$\frac{\Gamma \vdash t_1 : D \rightarrow A \quad \Gamma \vdash t_2 : B \rightarrow E}{\Gamma \vdash t_1 \rightarrow t_2 : (A \rightarrow B) \rightarrow (D \rightarrow E)} \text{PROD}$$

At this point it is straightforward to carry out the definition of Box_A and Unbox_A using the definitions from the model. Showing the admissibility of the typing and reduction rules follows by induction on A .

B.7 Proof of Left-to-Right Consistent Subtyping (Lemma 5.3)

This is a proof by induction on $\Gamma \vdash A \lesssim B$. We only show a few of the most interesting cases.

Case.

$$\frac{\Gamma \vdash A \lesssim S}{\Gamma \vdash A \lesssim ?} \text{box}$$

In this case $B = ?$.

Part i. Choose $A' = ?$.

Part ii. Choose $B' = A$.

Case.

$$\frac{\Gamma \vdash B \lesssim S}{\Gamma \vdash ? \lesssim B} \text{unbox}$$

In this case $A = ?$.

Part i. Choose $A' = B$.

Part ii. Choose $B' = ?$.

Case.

$$\frac{\Gamma \vdash A_2 \lesssim A_1 \quad \Gamma \vdash B_1 \lesssim B_2}{\Gamma \vdash (A_1 \rightarrow B_1) \lesssim (A_2 \rightarrow B_2)} \rightarrow$$

In this case $A = A_1 \rightarrow B_1$ and $B = A_2 \rightarrow B_2$.

Part i. By part two of the induction hypothesis we know that $\Gamma \vdash A'_1 \sim A_1$ and $\Gamma \vdash A_2 <: A'_1$, and by part one of the induction hypothesis $\Gamma \vdash B_1 \sim B'_1$ and $\Gamma \vdash B'_1 <: B_2$. By symmetry of type consistency we may conclude that $\Gamma \vdash A_1 \sim A'_1$ which along with $\Gamma \vdash B_1 \sim B'_1$ implies that $\Gamma \vdash (A_1 \rightarrow B_1) \sim (A'_1 \rightarrow B'_1)$, and by reapplying the rule we may conclude that $\Gamma \vdash (A'_1 \rightarrow B'_1) <: (A_2 \rightarrow B_2)$.

Part ii. Similar to part one, except that we first applying part one of the induction hypothesis to the first premise, and then the second part to the second premise.

B.8 Proof of Congruence of Type Consistency Along Type Precision (Lemma A.22)

The proofs of both parts are similar, and so we only show a few cases of the first part, but the omitted cases follow similarly.

Proof of part one. This is a proof by induction on the form of $A_1 \sqsubseteq A'_1$.

Case.

$$\frac{\Gamma \vdash A_1 \lesssim \mathbb{S}}{A_1 \sqsubseteq ?} ?$$

In this case $A'_1 = ?$. Suppose $\Gamma \vdash A_1 \sim A_2$. Then it suffices to show that $\Gamma \vdash ? \sim A_2$, and hence, we must show that $\Gamma \vdash A_2 \lesssim \mathbb{S}$, but this follows by Lemma A.20.

Case.

$$\frac{A \sqsubseteq C \quad B \sqsubseteq D}{(A \rightarrow B) \sqsubseteq (C \rightarrow D)} \rightarrow$$

In this case $A_1 = A \rightarrow B$ and $A'_1 = C \rightarrow D$. Suppose $\Gamma \vdash A_1 \sim A_2$. Then by inversion for type consistency it must be the case that either $A_2 = ?$ and $\Gamma \vdash A_1 \lesssim \mathbb{S}$, or $A_2 = A' \rightarrow B'$, $\Gamma \vdash A \sim A'$, and $\Gamma \vdash B \sim B'$.

Consider the former. Then it suffices to show that $\Gamma \vdash A'_1 \sim ?$, and hence we must show that $\Gamma \vdash A'_1 \lesssim \mathbb{S}$, but this follows from Lemma A.21.

Consider the case when $A_2 = A' \rightarrow B'$, $\Gamma \vdash A \sim A'$, and $\Gamma \vdash B \sim B'$. It suffices to show that $\Gamma \vdash (C \rightarrow D) \sim (A' \rightarrow B')$ which follows from $\Gamma \vdash A' \sim C$ and $\Gamma \vdash D \sim B'$. Thus, it suffices to show that latter. By assumption we know the following:

$$A \sqsubseteq C \text{ and } \Gamma \vdash A \sim A'$$

$$B \sqsubseteq D \text{ and } \Gamma \vdash B \sim B'$$

Now by two applications of the induction hypothesis we obtain $\Gamma \vdash C \sim A'$ and $\Gamma \vdash D \sim B'$. By symmetry the former implies $\Gamma \vdash A \sim C$ and we obtain our result.

B.9 Proof of Congruence of Subtyping Along Type Precision (Lemma A.24)

This is a proof by induction on the form of $A \sqsubseteq B$. The proof of part two follows similarly to part one. We only give the most interesting cases. All others follow similarly.

Proof of part one. We only show the most interesting case, because all others are similar.

Case.

$$\frac{A_1 \sqsubseteq A_2 \quad B_1 \sqsubseteq B_2}{(A_1 \rightarrow B_1) \sqsubseteq (A_2 \rightarrow B_2)} \rightarrow$$

In this case $A = A_1 \rightarrow B_1$ and $B = A_2 \rightarrow B_2$. Suppose $\Gamma \vdash A \lesssim C$. Thus, by inversion for consistency subtyping it must be the case that $C = \top$ and $\Gamma \vdash A : \star$, $C = ?$ and $\Gamma \vdash A \lesssim \mathbb{S}$, or $C = A'_1 \rightarrow B'_1$, $\Gamma \vdash A'_1 \lesssim A_1$, and $\Gamma \vdash B_1 \lesssim B'_1$. The case when $C = \top$ is trivial, and the case when $C = ?$ is similarly to the proof of Lemma A.22.

Consider the case when $C = A'_1 \rightarrow B'_1$, $\Gamma \vdash A'_1 \lesssim A_1$, and $\Gamma \vdash B_1 \lesssim B'_1$. By assumption we know the following:

$$A_1 \sqsubseteq A_2 \text{ and } \Gamma \vdash A'_1 \lesssim A_1$$

$$B_1 \sqsubseteq B_2 \text{ and } \Gamma \vdash B_1 \lesssim B'_1$$

So by part two and one, respectively, of the induction hypothesis we know that $\Gamma \vdash A'_1 \lesssim A_2$ and $\Gamma \vdash B_2 \lesssim B'_1$. Thus, by reapplying the rule above we may now conclude that $\Gamma \vdash (A_2 \rightarrow B_2) \lesssim (A'_1 \rightarrow B'_2)$ to obtain our result.

B.10 Proof of Gradual Guarantee Part One (Lemma 5.5)

This is a proof by induction on $\Gamma \vdash_{\text{SG}} t : A$. We only show the most interesting cases, because the others follow similarly.

Case.

$$\frac{x : A \in \Gamma \quad \Gamma \text{ Ok}}{\Gamma \vdash_{\text{SG}} x : A} \text{VAR}$$

In this case $t = x$. Suppose $t \sqsubseteq t'$. Then it must be the case that $t' = x$. If $x : A \in \Gamma$, then there is a type A' such that $x : A' \in \Gamma'$ and $A \sqsubseteq A'$. Thus, choose $B = A'$ and the result follows.

Case.

$$\frac{\Gamma \vdash_{\text{SG}} t_1 : A' \quad \text{nat}(A') = \text{Nat}}{\Gamma \vdash_{\text{SG}} \text{succ } t_1 : \text{Nat}} \text{succ}$$

In this case $A = \text{Nat}$ and $t = \text{succ } t_1$. Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. Then by definition it must be the case that $t' = \text{succ } t_2$ where $t_1 \sqsubseteq t_2$. By the induction hypothesis $\Gamma' \vdash_{\text{SG}} t_2 : B'$ where $A' \sqsubseteq B'$. Since $\text{nat}(A') = \text{Nat}$ and $A' \sqsubseteq B'$, then it must be the case that $\text{nat}(B') = \text{Nat}$ by Lemma A.16. At this point we obtain our result by choosing $B = \text{Nat}$, and reapplying the rule above.

Case.

$$\frac{\begin{array}{l} \Gamma \vdash_{\text{SG}} t_1 : C \quad \text{nat}(C) = \text{Nat} \quad \Gamma \vdash A_1 \sim A \\ \Gamma \vdash_{\text{SG}} t_2 : A_1 \quad \Gamma, x : \text{Nat} \vdash_{\text{SG}} t_3 : A_2 \quad \Gamma \vdash A_2 \sim A \end{array}}{\Gamma \vdash_{\text{SG}} \text{case } t_1 \text{ of } 0 \rightarrow t_2, (\text{succ } x) \rightarrow t_3 : A} \text{Nat}_e$$

In this case $t = \text{case } t_1 \text{ of } 0 \rightarrow t_2, (\text{succ } x) \rightarrow t_3$. Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. This implies that $t' = \text{case } t'_1 \text{ of } 0 \rightarrow t'_2, (\text{succ } x) \rightarrow t'_3$ such that $t_1 \sqsubseteq t'_1$, $t_2 \sqsubseteq t'_2$, and $t_3 \sqsubseteq t'_3$. Since $\Gamma \sqsubseteq \Gamma'$ then $(\Gamma, x : \text{Nat}) \sqsubseteq (\Gamma', x : \text{Nat})$. By the induction hypothesis we know the following:

$$\Gamma' \vdash_{\text{SG}} t'_1 : C' \text{ for } C \sqsubseteq C'$$

$$\Gamma' \vdash_{\text{SG}} t_2 : A'_1 \text{ for } A_1 \sqsubseteq A'_1$$

$$\Gamma', x : \text{Nat} \vdash_{\text{SG}} t_3 : A'_2 \text{ for } A_2 \sqsubseteq A'_2$$

By assumption we know that $\Gamma \vdash A_1 \sim A$, $\Gamma \vdash A_2 \sim A$, and $\Gamma \sqsubseteq \Gamma'$, hence, by Lemma A.18 we know $\Gamma' \vdash A_1 \sim A$ and $\Gamma' \vdash A_2 \sim A$. By the induction hypothesis we know that $A_1 \sqsubseteq A'_1$ and $A_2 \sqsubseteq A'_2$, so by using Lemma A.17 we

may obtain that $\Gamma' \vdash A'_1 \sim A$ and $\Gamma' \vdash A'_2 \sim A$. At this point choose $B = A$ and we obtain our result by reapplying the rule.

Case.

$$\frac{\Gamma \vdash_{\text{SG}} t_1 : A_1 \quad \Gamma \vdash_{\text{SG}} t_2 : A_2 \quad \text{list}(A_2) = \text{List } A_3 \quad \Gamma \vdash A_1 \sim A_3}{\Gamma \vdash_{\text{SG}} t_1 :: t_2 : \text{List } A_3} \text{List}_i$$

In this case $A = \text{List } A_3$ and $t = t_1 :: t_2$. Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. Then it must be the case that $t' = t'_1 :: t'_2$ where $t_1 \sqsubseteq t'_1$ and $t_2 \sqsubseteq t'_2$. Then by the induction hypothesis we know the following:

$$\Gamma' \vdash_{\text{SG}} t'_1 : A'_1 \text{ where } A_1 \sqsubseteq A'_1$$

$$\Gamma' \vdash_{\text{SG}} t'_2 : A'_2 \text{ where } A_2 \sqsubseteq A'_2$$

By Lemma A.16 $\text{list}(A'_2) = \text{List } A'_3$ where $A_3 \sqsubseteq A'_3$. Now by Lemma A.18 and Lemma A.17 we know that $\Gamma' \vdash A'_1 \sim A_3$, and by using the same lemma again, $\Gamma' \vdash A'_1 \sim A'_3$ because $\Gamma' \vdash A_3 \sim A'_1$ holds by symmetry. Choose $B = \text{List } A'_3$ and the result follows.

Case.

$$\frac{\Gamma \vdash_{\text{SG}} t_1 : A_1 \quad \Gamma \vdash_{\text{SG}} t_2 : A_2}{\Gamma \vdash_{\text{SG}} (t_1, t_2) : A_1 \times A_2} \times_i$$

In this case $A = A_1 \times A_2$ and $t = (t_1, t_2)$. Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. This implies that $t' = (t'_1, t'_2)$ where $t_1 \sqsubseteq t'_1$ and $t_2 \sqsubseteq t'_2$.

By the induction hypothesis we know:

$$\Gamma' \vdash_{\text{SG}} t'_1 : A'_1 \text{ and } A_1 \sqsubseteq A'_1$$

$$\Gamma' \vdash_{\text{SG}} t'_2 : A'_2 \text{ and } A_2 \sqsubseteq A'_2$$

Then choose $B = A'_1 \times A'_2$ and the result follows by reapplying the rule above and the fact that $(A_1 \times A_2) \sqsubseteq (A'_1 \times A'_2)$.

Case.

$$\frac{\Gamma, x : A_1 \vdash_{\text{SG}} t_1 : B_1}{\Gamma \vdash_{\text{SG}} \lambda(x : A_1).t_1 : A_1 \rightarrow B_1} \rightarrow_i$$

In this case $A_1 \rightarrow B_2$ and $t = \lambda(x : A_1).t_1$. Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. Then it must be the case that $t' = \lambda(x : A_2).t_2$, $t_1 \sqsubseteq t_2$, and $A_1 \sqsubseteq A_2$. Since $\Gamma \sqsubseteq \Gamma'$ and $A_1 \sqsubseteq A_2$, then $(\Gamma, x : A_1) \sqsubseteq (\Gamma', x : A_2)$ by definition. Thus, by the induction hypothesis we know the following:

$$\Gamma', x : A_2 \vdash_{\text{SG}} t'_1 : B_2 \text{ and } B_1 \sqsubseteq B_2$$

Choose $B = A_2 \rightarrow B_2$ and the result follows by reapplying the rule above and the fact that $(A_1 \rightarrow B_1) \sqsubseteq (A_2 \rightarrow B_2)$.

Case.

$$\frac{\Gamma \vdash_{\text{SG}} t_1 : \forall(X <: C_0).C_2 \quad \Gamma \vdash C_1 \lesssim C_0}{\Gamma \vdash_{\text{SG}} [C_1]t_1 : [C_1/X]C_2} \forall_e$$

In this case $t = [C_1]t_1$. Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. Then it must be the case that $t' = [C'_1]t_2$ such that $t_1 \sqsubseteq t_2$ and $C_1 \sqsubseteq C'_1$. By the induction hypothesis:

$$\Gamma' \vdash_{\text{SG}} t_2 : C \text{ where } \forall(X <: C_0).C_2 \sqsubseteq C$$

Thus, it must be the case that $C = \forall(X <: C_0).C'_2$ such that $C_2 \sqsubseteq C'_2$. By assumption we know that $\Gamma \vdash C_1 \lesssim C_0$ and $C_1 \sqsubseteq C'_1$, and thus, by Corollary A.25 and Lemma A.19 we know $\Gamma' \vdash C'_1 \lesssim C_0$. Thus, choose $B = C$, and the result follows by reapplying the rule above, and the fact that $A \sqsubseteq C$, because $C_2 \sqsubseteq C'_2$.

Case.

$$\frac{\Gamma \vdash_{\text{SG}} t : A' \quad \Gamma \vdash A' \lesssim A}{\Gamma \vdash_{\text{SG}} t : A} \text{SUB}$$

Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. By the induction hypothesis we know that $\Gamma' \vdash_{\text{SG}} t' : A''$ for $A' \sqsubseteq A''$. We know $A'' \sqsubseteq A$ or $A \sqsubseteq A''$, because we know that $\Gamma \vdash A' \lesssim A$ and $A' \sqsubseteq A''$. Suppose $A'' \sqsubseteq A$, then by Corollary A.11 $\Gamma' \vdash A'' \lesssim A$, and then by subsumption $\Gamma' \vdash_{\text{SG}} t' : A$, hence, choose $B = A$ and the result follows. If $A \sqsubseteq A''$, then choose $B = A''$ and the result follows.

Case.

$$\frac{\Gamma \vdash_{\text{SG}} t_1 : C \quad \text{fun}(C) = A_1 \rightarrow B_1 \quad \Gamma \vdash_{\text{SG}} t_2 : A_2 \quad \Gamma \vdash A_2 \sim A_1}{\Gamma \vdash_{\text{SG}} t_1 t_2 : B_1} \rightarrow_e$$

In this case $A = B_1$ and $t = t_1 t_2$. Suppose $t \sqsubseteq t'$ and $\Gamma \sqsubseteq \Gamma'$. The former implies that $t' = t'_1 t'_2$ such that $t_1 \sqsubseteq t'_1$ and $t_2 \sqsubseteq t'_2$. By the induction hypothesis we know the following:

$$\Gamma' \vdash_{\text{SG}} t'_1 : C' \text{ for } C \sqsubseteq C'$$

$$\Gamma' \vdash_{\text{SG}} t'_2 : A'_2 \text{ for } A_2 \sqsubseteq A'_2$$

We know by assumption that $\Gamma \vdash A_2 \sim A_1$ and hence $\Gamma' \vdash A_2 \sim A_1$ because bounds on type variables are left unchanged by context precision. Since $C \sqsubseteq C'$ and $\text{fun}(C) = A_1 \rightarrow B_1$, then $\text{fun}(C') = A'_1 \rightarrow B'_1$ where $A_1 \sqsubseteq A'_1$ and $B_1 \sqsubseteq B'_1$ by Lemma A.16. Furthermore, we know $\Gamma' \vdash A_2 \sim A_1$ and $A_2 \sqsubseteq A'_2$ and $A_1 \sqsubseteq A'_1$, then we know $\Gamma' \vdash A'_2 \sim A'_1$ by Corollary A.23. So choose $B = B'_1$. Then reapply the rule above and the result follows, because $B_1 \sqsubseteq B'_1$.

B.11 Proof of Type Preservation for Cast Insertion (Lemma 5.6)

The cast insertion algorithm is type directed and with respect to every term t_1 it will produce a term t_2 of the core language with the type A – this is straightforward to show by induction on the form of $\Gamma \vdash_{\text{SG}} t_1 : A$ making use of typing for casting morphisms Lemma A.26 – except in the case of type application. We only consider

this case here.

This is a proof by induction on the form of $\Gamma \vdash_{\text{SG}} t_1 : A$. Suppose the form of $\Gamma \vdash_{\text{SG}} t_1 : A$ is as follows:

$$\frac{\Gamma \vdash_{\text{SG}} t'_1 : \forall(X <: B_1).B_2 \quad \Gamma \vdash A_1 \lesssim B_1}{\Gamma \vdash_{\text{SG}} [A_1]t'_1 : [A_1/X]B_2} \forall_e$$

In this case $t_1 = [A_1]t'_1$ and $A = [A_1/X]B_2$. Cast insertion is syntax directed, and hence, inversion for it holds trivially. Thus, it must be the case that the form of $\Gamma \vdash t_1 \Rightarrow t_2 : B$ is as follows:

$$\frac{\Gamma \vdash t'_1 \Rightarrow t'_2 : \forall(X <: B_1).B'_2 \quad \Gamma \vdash A_1 \sim A_2 \quad \Gamma \vdash A_2 <: B_1}{\Gamma \vdash ([A_1]t'_1) \Rightarrow ([A_2]t'_2) : [A_2/X]B'_2}$$

So $t_2 = [A_2]t'_2$ and $B = [A_2/X]B'_2$. Since we know $\Gamma \vdash_{\text{SG}} t'_1 : \forall(X <: B_1).B_2$ and $\Gamma \vdash t'_1 \Rightarrow t'_2 : \forall(X <: B_1).B'_2$ we can apply the induction hypothesis to obtain $\Gamma \vdash_{\text{CG}} t'_2 : \forall(X <: B_1).B'_2$ and $\Gamma \vdash (\forall(X <: B_1).B_2) \sim (\forall(X <: B_1).B'_2)$, and thus, $\Gamma, X <: B_1 \vdash B_2 \sim B'_2$ by inversion for type consistency. If $\Gamma, X <: B_1 \vdash B_2 \sim B'_2$ holds, then $\Gamma \vdash [A_1/X]B_2 \sim [A_2/X]B'_2$ when $\Gamma \vdash A_1 \sim A_2$ by substitution for type consistency (Lemma A.29). Since we know $\Gamma \vdash_{\text{CG}} t'_2 : \forall(X <: B_1).B'_2$ by the induction hypothesis and $\Gamma \vdash A_2 <: B_1$ by assumption, then we know $\Gamma \vdash_{\text{CG}} [A_2]t'_2 : [A_2/X]B'_2$ by applying the Core Grady typing rule \forall_e .

B.12 Proof of Simulation of More Precise Programs (Lemma 5.8)

This is a proof by induction on $\Gamma \vdash_{\text{CG}} t_1 : A_1$. We only give the most interesting cases. All others follow similarly. Throughout the proof we implicitly make use of typability inversion (Lemma A.32) when applying the induction hypothesis.

Case.

$$\frac{\Gamma \vdash_{\text{CG}} t : \text{Nat}}{\Gamma \vdash_{\text{CG}} \text{succ } t : \text{Nat}} \text{succ}$$

In this case $t_1 = \text{succ } t$ and $A = \text{Nat}$. Suppose $\Gamma \vdash_{\text{CG}} t'_1 : A'$. By inversion for term precision we must consider the following cases:

- i. $t'_1 = \text{succ } t'$ and $\Gamma \vdash t \sqsubseteq t'$
- ii. $t'_1 = \text{box}_{\text{Nat}} t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : \text{Nat}$

Proof of part i. Suppose $t'_1 = \text{succ } t'$, $\Gamma \vdash t \sqsubseteq t'$, and $t_1 \rightsquigarrow t_2$. Then $t_2 = \text{succ } t''$ and $t \rightsquigarrow t''$. Then by the induction hypothesis we know that there is some t''' such that $t' \rightsquigarrow^* t'''$ and $\Gamma \vdash t'' \sqsubseteq t'''$. Choose $t'_2 = \text{succ } t'''$ and the result follows.

Proof of part ii. Suppose $t'_1 = \text{box}_{\text{Nat}} t_1$, $\Gamma \vdash_{\text{CG}} t_1 : \text{Nat}$, and $t_1 \rightsquigarrow t_2$. Then choose $t'_2 = \text{box}_{\text{Nat}} t_2$, and the result follows, because we know by type preservation that $\Gamma \vdash_{\text{CG}} t_2 : \text{Nat}$, and hence, $\Gamma \vdash t_2 \sqsubseteq t'_2$.

Case.

$$\frac{\begin{array}{c} \Gamma \vdash_{\text{CG}} t : \text{Nat} \\ \Gamma \vdash_{\text{CG}} t_3 : A \quad \Gamma, x : \text{Nat} \vdash_{\text{CG}} t_4 : A \end{array}}{\Gamma \vdash_{\text{CG}} \text{case } t : \text{Nat of } 0 \rightarrow t_3, (\text{succ } x) \rightarrow t_4 : A} \text{Nat}_e$$

In this case $t_1 = \text{case } t : \text{Nat of } 0 \rightarrow t_3, (\text{succ } x) \rightarrow t_4$. Suppose $\Gamma \vdash_{\text{CG}} t'_1 : A'$. Then inversion of term precision implies that one of the following must hold:

- $t'_1 = \text{case } t' : \text{Nat of } 0 \rightarrow t'_3, (\text{succ } x) \rightarrow t'_4$, $\Gamma \vdash t \sqsubseteq t'$, $\Gamma \vdash t_3 \sqsubseteq t'_3$, and $\Gamma, x : \text{Nat} \vdash t_4 \sqsubseteq t'_4$
- $t'_1 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
- $t'_1 = \text{squash}_K t_1$, $\Gamma \vdash_{\text{CG}} t_1 : K$, and $A = K$

Proof of part i. Suppose $t'_1 = \text{case } t' : \text{Nat of } 0 \rightarrow t'_3, (\text{succ } x) \rightarrow t'_4$, $\Gamma \vdash t \sqsubseteq t'$, $\Gamma \vdash t_3 \sqsubseteq t'_3$, and $\Gamma, x : \text{Nat} \vdash t_4 \sqsubseteq t'_4$.

We case split over $t_1 \rightsquigarrow t_2$.

Case. Suppose $t = 0$ and $t_2 = t_3$. Since $\Gamma \vdash t_1 \sqsubseteq t'_1$ we know that it must be the case that $t' = 0$ and $t'_1 \rightsquigarrow t'_3$ by inversion for term precision or t'_1 would not be typable which is a contradiction. Thus, choose $t'_2 = t'_3$ and the result follows.

Case. Suppose $t = \text{succ } t''$ and $t_2 = [t''/x]t_4$. Since $\Gamma \vdash t_1 \sqsubseteq t'_1$ we know that $t' = \text{succ } t'''$, or t'_1 would not be typable, and $\Gamma \vdash t'' \sqsubseteq t'''$ by inversion for term precision. In addition, $t'_1 \rightsquigarrow [t'''/x]t'_4$. Choose $t_2 = [t'''/x]t'_4$. Then it suffices to show that $\Gamma \vdash [t''/x]t_4 \sqsubseteq [t'''/x]t'_4$ by substitution for term precision (Lemma A.31).

Case. Suppose a congruence rule was used. Then $t_2 = \text{case } t'' : \text{Nat of } 0 \rightarrow t''_3, (\text{succ } x) \rightarrow t''_4$. This case will follow straightforwardly by induction and a case split over which congruence rule was used.

Proof of part ii. Suppose $t'_1 = \text{box}_A t_1$, $\Gamma \vdash_{\text{CG}} t_1 : A$, and $t_1 \rightsquigarrow t_2$. Then choose $t'_2 = \text{box}_A t_2$, and the result follows, because we know by type preservation that $\Gamma \vdash_{\text{CG}} t_2 : A$, and hence, $\Gamma \vdash t_2 \sqsubseteq t'_2$.

Proof of part iii. Similar to the previous case.

Case.

$$\frac{\Gamma \vdash_{\text{CG}} t : A \times B}{\Gamma \vdash_{\text{CG}} \text{fst } t : A} \times_{e1}$$

In this case $t_1 = \text{fst } t$. Suppose $\Gamma \vdash t_1 \sqsubseteq t'_1$ and $\Gamma \vdash_{\text{CG}} t'_1 : A'$. Then inversion for term precision implies that one of the following must hold:

- $t'_1 = \text{fst } t'$ and $\Gamma \vdash t \sqsubseteq t'$
- $t'_1 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
- $t'_1 = \text{squash}_K t_1$, $\Gamma \vdash_{\text{CG}} t_1 : K$, and $A = K$

We only consider the proof of part i, because the others follow similarly to the previous case. Case split over $t_1 \rightsquigarrow t_2$.

Case. Suppose $t = (t'_3, t''_3)$ and $t_2 = t'_3$. By inversion for term precision it must be the case that $t' = (t'_4, t''_4)$ because $\Gamma \vdash t_1 \sqsubseteq t'_1$ or else t'_1 would not

be typable. In addition, this implies that $\Gamma \vdash t'_3 \sqsubseteq t'_4$ and $\Gamma \vdash t''_3 \sqsubseteq t''_4$. Thus, $t'_1 \rightsquigarrow t'_4$. Thus, choose $t'_2 = t'_4$ and the result follows.

Case. Suppose a congruence rule was used. Then $t_2 = \text{fst } t''$. This case will follow straightforwardly by induction and a case split over which congruence rule was used.

Case.

$$\frac{\Gamma, x : A_1 \vdash_{\text{CG}} t : A_2}{\Gamma \vdash_{\text{CG}} \lambda(x : A_1).t : A_1 \rightarrow A_2} \rightarrow_i$$

In this case $t_1 = \lambda(x : A_1).t$ and $A = A_1 \rightarrow A_2$. Suppose $\Gamma \vdash t_1 \sqsubseteq t'_1$ and $\Gamma \vdash_{\text{CG}} t'_1 : A'$. Then inversion of term precision implies that one of the following must hold:

- $t'_1 = \lambda(x : A'_1).t'$
- $t'_1 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
- $t'_1 = \text{squash}_K t_1$, $\Gamma \vdash_{\text{CG}} t_1 : K$, and $A = K$

We only consider the proof of part i. The reduction relation does not reduce under λ -expressions. Hence, $t_2 = t_1$, and thus, choose $t'_2 = t'_1$, and the case trivially follows.

Case.

$$\frac{\Gamma \vdash_{\text{CG}} t_3 : A_1 \rightarrow A_2 \quad \Gamma \vdash_{\text{CG}} t_4 : A_1}{\Gamma \vdash_{\text{CG}} t_3 t_4 : A_2} \rightarrow_e$$

In this case $t_1 = t_3 t_4$. Suppose $\Gamma \vdash t_1 \sqsubseteq t'_1$ and $\Gamma \vdash_{\text{CG}} t'_1 : A'$. Then by inversion for term precision we know one of the following is true:

- i. $t'_1 = t'_3 t'_4$, $\Gamma \vdash t_3 \sqsubseteq t'_3$, and $\Gamma \vdash t_4 \sqsubseteq t'_4$
- ii. $t'_1 = \text{box}_{A_2} t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
- iii. $t_3 = \text{unbox}_{A_2} t'_1$, $t'_1 = t_4$, and $\Gamma \vdash_{\text{CG}} t_4 : ?$
- iv. $t_3 = \text{split}_{K_2} t'_1$, $t'_1 = t_4$, and $\Gamma \vdash_{\text{CG}} t_4 : ?$
- v. $t'_1 = \text{squash}_{K_2} t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : K_2$

Proof of part i. Suppose $t'_1 = t'_3 t'_4$, $\Gamma \vdash t_3 \sqsubseteq t'_3$, and $\Gamma \vdash t_4 \sqsubseteq t'_4$.

We case split on the form of $t_1 \rightsquigarrow t_2$.

Case. Suppose $t_3 = \lambda(x : A_1).t_5$ and $t_2 = [t_4/x]t_5$. Then by inversion for term precision we know that $t'_3 = \lambda(x : A'_1).t'_5$ and $\Gamma, x : A'_2 \vdash t_5 \sqsubseteq t'_5$, because $\Gamma \vdash t_3 \sqsubseteq t'_3$ and the requirement that t'_1 is typable. Choose $t'_2 = [t'_4/x]t'_5$ and it is easy to see that $t'_1 \rightsquigarrow [t'_4/x]t'_5$. We know that $\Gamma, x : A'_2 \vdash t_5 \sqsubseteq t'_5$ and $\Gamma \vdash t_4 \sqsubseteq t'_4$, and hence, by Lemma A.31 we know that $\Gamma \vdash [t_4/x]t_5 \sqsubseteq [t'_4/x]t'_5$, and we obtain our result.

Case. Suppose $t_3 = \text{unbox}_A$, $t_4 = \text{box}_A t_5$, and $t_2 = t_5$. Then by inversion for term precision $t'_3 = \text{unbox}_A$, $t'_4 = \text{box}_A t'_5$, and $\Gamma \vdash t_5 \sqsubseteq t'_5$. Note that $t'_4 = \text{box}_A t'_5$ and $\Gamma \vdash t_5 \sqsubseteq t'_5$ hold even though there are two potential rules that could have been used to construct $\Gamma \vdash t_4 \sqsubseteq t'_4$. Choose $t'_2 = t'_5$ and it is easy to see that $t'_1 \rightsquigarrow t'_5$. Thus, we obtain our result.

Case. Suppose $t_3 = \text{unbox}_A$, $t_4 = \text{box}_B t_5$, $A \neq B$, and $t_2 = \text{error}_B$. Then $t'_3 = \text{unbox}_A$ and $t'_4 = \text{box}_B t'_5$. Choose $t'_2 = \text{error}_B$ and it is easy to see that

$t'_1 \rightsquigarrow t'_5$. Finally, we can see that $\Gamma \vdash t_2 \sqsubseteq t'_2$ by reflexivity.

Case. Suppose $t_3 = \text{split}_U$, $t_4 = \text{squash}_U t_5$, and $t_2 = t_5$. Similar to the case for boxing and unboxing.

Case. Suppose $t_3 = \text{split}_{U_1}$, $t_4 = \text{squash}_{U_2} t_5$, $U_1 \neq U_2$, and $t_2 = t_5$. Similar to the case for boxing and unboxing.

Case. Suppose a congruence rule was used. Then $t_2 = t'_5 t'_6$. This case will follow straightforwardly by induction and a case split over which congruence rule was used.

Proof of part ii. We know that $t_1 = t_3 t_4$. Suppose $t'_1 = \text{box}_{A_2} t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$. If $t_1 \rightsquigarrow t_2$, then $t'_1 = (\text{box}_{A_2} t_1) \rightsquigarrow (\text{box}_{A_2} t_2)$. Thus, choose $t'_2 = \text{box}_{A_2} t_2$.

Proof of part iii. We know that $t_1 = t_3 t_4$. Suppose $t_3 = \text{unbox}_{A_2}$, $t'_1 = t_4$, and $\Gamma \vdash_{\text{CG}} t_4 : ?$. Then $t_1 = \text{unbox}_{A_2} t_4$. We case split over $t_1 \rightsquigarrow t_2$. We have three cases to consider.

Suppose $t_4 = \text{box}_{A_2} t_5$ and $t_2 = t_5$. Then choose $t'_2 = t_4 = t'_1$, and we obtain our result.

Suppose $t_4 = \text{box}_{A_3} t_5$, $A_2 \neq A_3$, and $t_2 = \text{error}_{A_2}$. Then choose $t'_2 = t_4 = t'_1$, and we obtain our result.

Suppose a congruence rule was used. Then $t_2 = t_3 t'_4$. This case will follow straightforwardly by induction.

Proof of part iv. Similar to part iii.

Proof of part v. Similar to part ii.

Case.

$$\frac{\Gamma \vdash_{\text{CG}} t : \forall (X <: A_2). A_3 \quad \Gamma \vdash A_1 <: A_2}{\Gamma \vdash_{\text{CG}} [A_1]t : [A_1/X]A_3} \forall_e$$

In this case $t_1 = [A_1]t$ and $A = [A_1/X]A_3$. Suppose $\Gamma \vdash t_1 \sqsubseteq t'_1$ and $\Gamma \vdash_{\text{CG}} t'_1 : A'$.

- $t'_1 = [A'_1]t'$, $\Gamma \vdash t \sqsubseteq t'$, and $A_1 \sqsubseteq A'_1$
- $t'_1 = \text{box}_A t_1$ and $\Gamma \vdash_{\text{CG}} t_1 : A$
- $t'_1 = \text{squash}_K t_1$, $\Gamma \vdash_{\text{CG}} t_1 : K$, and $A = K$

We only consider the proof of part i. We case split over the form of $t_1 \rightsquigarrow t_2$.

Case. Suppose $t = \Lambda(X <: A_2). t_3$ and $t_2 = [A_1/X]t_3$. Then inversion for term precision on $\Gamma \vdash t \sqsubseteq t'$ and the fact that $\Gamma \vdash_{\text{CG}} t : \forall (X <: A_2). A_3$ and $t'_1 = [A'_1]t'$ then it can only be the case that $t' = \Lambda(X <: A_2). t'_3$ and $\Gamma, X <: A_2 \vdash t_3 \sqsubseteq t'_3$, or t'_1 would not be typable which is a contradiction. Then by substitution for term precision we know that $\Gamma \vdash [A_1/X]t_3 \sqsubseteq [A'_1/X]t'_3$ by substitution for term precision (Lemma A.31), because we know that

$A_1 \sqsubseteq A'_1$. Choose $t'_2 = [A'_1/X]t'_3$ and the result follows, because $t'_1 \rightsquigarrow t'_2$.

Case. Suppose a congruence rule was used. Then $t_2 = [A_1]t''$. This case will follow straightforwardly by induction and a case split over which congruence rule was used.

Case.

$$\frac{\Gamma \vdash_{\text{CG}} t : A_1 \quad \Gamma \vdash A_1 <: A_2}{\Gamma \vdash_{\text{CG}} t : A_2} \text{SUB}$$

In this case $t_1 = t$ and $A = A_2$. Suppose $\Gamma \vdash t_1 \sqsubseteq t'_1$ and $\Gamma \vdash_{\text{CG}} t'_1 : A'$. Assume $t_1 \rightsquigarrow t_2$. Then by the induction hypothesis there is a t'_2 such that $t'_1 \rightsquigarrow^* t'_2$ and $\Gamma \vdash t_2 \sqsubseteq t'_2$, thus, we obtain our result.