

Parametricity and Free Theorems for Nested Types

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Abstract goes here

1 INTRODUCTION

Suppose we wanted to prove some property of programs over an algebraic data type (ADT) such as that of lists, coded in Agda as

```
data List (A : Set) : Set where
  nil : List A
  Cons : A → List A → List A
```

A natural approach to the problem uses structural induction on the input data structure in question. This requires knowing not just the definition of the ADT of which the input data structure is an instance, but also the program text for the functions involved in the properties to be proved. For example, to prove by induction that mapping a polymorphic function over a list and then reversing the resulting list is the same as reversing the original list and then mapping the function over the result, we unwind the (recursive) definitions of the reverse and map functions over lists to according to the inductive structure of the input list. Such data-driven induction proofs over ADTs are so routine that they are often included in, say, undergraduate functional programming courses.

An alternative technique for proving results like the above map-reverse property for lists is to use parametricity, a formalization of extensional type-uniformity in polymorphic languages. Parametricity was originally put forth by Reynolds [Reynolds 1983] for System F [Girard et al. 1989], the formal calculus at the core of all polymorphic functional languages. It was later popularized — for an informal Haskell-like language that is essentially System F augmented with list types defined natively as type-level fixpoints — by Wadler as his so-called “theorems for free” [Walder 1989] because it allows the deduction of many properties of programs in such languages solely from their types. In particular, the deductions require no knowledge whatsoever of the text of the programs involved. While most of the free theorems appearing in Wadler’s paper are essentially naturality properties of polymorphic functions, parametricity can also be used to prove properties, like correctness of the program optimization for lists and other ADTs known as *short cut fusion* [Gill et al. 1993; Johann 2002, 2003], that go beyond simple naturality. In addition, parametricity in the presence of ADTs **check!** has further been used to prove i) *properties of programs*, e.g., that they perform no illegal operations, satisfy certain security criteria [??], or are observationally equivalent to their compiled forms [?]; ii) *whole-language properties*, e.g., that they support data abstraction and modularity via representation independence, [????], enforce information flow policies [?], or guarantee privacy [?]; and iii) *properties of implementations*, e.g., compiler correctness [????]. Parametricity is thus an important tool for reasoning about programs in polymorphic languages that natively support ADTs. **Be clear about what this means. Re-word?**

This paper is about parametricity for a polymorphic language supporting not just ADTs, but nested types as well. An ADT defines a *family of inductive data types*, one for each input type. For example, the List data type definition above defines a collection of data types List A, List B, List (A × B), List (List A), etc., each independent of all the others. By contrast, a nested type [Bird and Meertens 1998] is an *inductive family of data types* that is defined over, or is defined mutually recursively with, (other) such data types. Since the structures of the data type at one type can depend on those at other types, the entire family of types must be defined at once. Examples of

```

reversePTree : ∀{A : Set} → PTree A → PTree A
reversePTree {A} = foldPTree {A} {PTree}
  pleaf
  (λp → pnode (mapPTree swap p))

foldPTree : ∀{A : Set} → {F : Set → Set} →
  ({B : Set} → B → FB) →
  ({B : Set} → F(B × B) → FB)
  → PTree A → F A
foldPTree n c (pleaf x) = n x
foldPTree n c (pnode p) = c (foldPTree n c p)

mapPTree : ∀{AB : Set} → (A → B) → PLeaves A → PLeaves B
mapPTree f (pleaf x) = pleaf (f x)
mapPTree f (pnode p) = pnode (mapPTree f p)

swap : ∀{A : Set} → (A × A) → (A × A)
swap (x, y) = (y, x)

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Fig. 1. reversePTree and auxiliary functions in Agda

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reverseBush : ∀{A : Set} → Bush A → Bush A
reverseBush {A} = bfold {A} {Bush} bnul balg

bfold : ∀{A : Set} → {F : Set → Set} →
  ({B : Set} → FB) →
  ({B : Set} → B → F (F B) → F B) →
  Bush A → F A
bfold bn bc bnul = bn
bfold bn bc (bcons x bb) =
  bc x (bfold bn bc (bmap (bfold bn bc) bb))

balg : ∀{B : Set} → B → Bush (Bush B) → Bush B
balg x bnul = bcons x bnul
balg x (bcons bnul bbbx) = bcons x (bcons bnul bbbx)
balg x (bcons (bcons y bx) bbbx) =
  bcons y (bcons (bcons x bx) bbbx)

```

Fig. 2. reverseBush and auxiliary functions in Agda

nested types include, trivially, ordinary ADTs, such as list and tree types; simple nested types, such as the data type

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data PTree (A : Set) : Set where
  pleaf : A → PTree A
  pnode : PTree (A × A) → PTree A

```

of perfect trees, whose recursive occurrences never appear below other type constructors; “deep” nested types [Johann and Polonsky 2020], such as the data type

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data Forest (A : Set) : Set where
  fempty : Forest A
  fnode : A → PTree (Forest A)

```

of perfect forests, whose recursive occurrences appear below type constructors for other nested types; and truly nested types¹, such as the data type

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data Bush (A : Set) : Set where
  bnul : Bush A
  bcons : A → Bush (Bush A) → Bush A

```

of bushes (also called *bootstrapped heaps* in [Okasaki 1999]), whose recursive occurrences appear below their own type constructors.

Suppose we wanted to prove properties of functions over nested types. We might, for example, want to prove a map-reverse property for the functions on perfect trees in Figure 1 or those on bushes in Figure 2. A few well-chosen examples quickly convince us that such a property should indeed hold for perfect trees and, taking inspiration from the ADT world, we could construct a proof by induction on the input perfect tree. In fact, to formally establish this result, we could prove it in Coq or Agda; indeed, both actually generate an induction rule for PTrees, and the generated rule gives the expected result because proving properties of perfect trees requires only that we induct over the top-level perfect tree in the recursive position, leaving any data internal to the input tree untouched. It is nowhere near as clear that analogous plausibility or inductive arguments can be made for the analogous property for bushes, since a proof by induction must recursively induct over the bushes that are internal to the top-level bush in the recursive position,

but it turns out they can.

¹Nested types that are defined over themselves are known as *truly nested types*.

since a proof by induction must recursively induct over the bushes that are internal to the top-level bush in the recursive position. This is sufficiently delicate that no induction rule for bushes or other truly nested types was known until very recently, when the *deep induction rules* of [Johann and Polonsky 2020] finally gave a way to induct over *all* of the structured data present in a structure. Deep induction thus not only gave the first principled, data type generic, and practically useful structural induction rules for bushes and other truly nested types, but has also opened the way for incorporating automatic generation of useful induction rules for (truly) nested data types — and, eventually, even GADTs — into modern proof assistants.

Mention {`—#TERMINATING#—`}

But recalling that inductive proofs over ADTs can sometimes be circumvented in the presence of parametricity, we might naturally ask if it isn't possible to prove properties of functions over nested types via parametricity. This paper answers this question in the affirmative, thus extending Wadler's party trick from ADTs to the richer family of nested types. To achieve this, we first introduce in Section ?? a polymorphic calculus supporting nested types as generated by the grammar of [Johann and Polonsky 2019]. At the type level, the calculus is the level-2-truncated version of the data type calculus from [Johann and Polonsky 2019]; the class of nested types it supports is very robust and includes all (truly) nested types known from the literature. We then construct a parametric model for our calculus. Our interpretations of types rely on the result from [Johann and Polonsky 2019] ensuring that all of the data types that can be represented in our calculus have well-defined semantics appropriately structured categories. Our term calculus is, as far as we know, entirely new. It features primitive constructs for functors, their initial algebras, and structured recursion (map, in, and fold, respectively), but does not support general recursion at the term level. It is strongly normalizing. Finally, we formulate in our calculus, and prove, a variety of free theorems for nested types. We prove not only *actually one generic theorem* naturality-style free theorems in Section ??, including those described above, but also give a formal proof of the short cut fusion for nested types first proposed in [?] in Section ??.

Reynolds, parametricity, Abstraction Theorem vs logical relations, etc.

Restriction of recursion to that expressible via fold limits the functions that can be written, but also provides strong termination guarantees.

In fact, we do much more than just build a parametric model for this calculus. The relationship between parametricity and naturality has long been of interest. By incorporating explicit Nat-types at the object level and interpreting them as natural transformations, our calculus allows us to clearly distinguish between what standard consequences of parametricity — like most of Wadler's — are really consequences of naturality and which — like free theorems for the type of filter for lists, ADTs, and even nested types, or the standard short cut fusion for ADTs and its extension, new here, to nested types, or non-existence of terms of bottom type, or uniqueness of terms of the type of the polymorphic identity function — actually go beyond naturality. This is made explicit in Enrico's subst theorem, which is an equality that is simply a consequence of our semantics and would hold even in a non-parametric model (i.e., one that didn't include the extra condition in the Set interpretation of Nat-types), and does not in any way reply on the abstraction theorem. (We will undoubtedly have to mention Bernardy et al. if we mention internalizing parametricity...)

Enrico's subst theorem is actually very general. Generic over data types, functors over which data types are built in Nat-types, and functions of Nat-type.

Foralls in Nat-types are at the object level, whereas the foralls in contexts are at the meta-level. So par results in subst theorem internalize parametricity in the calculus, whereas those parametricity results that do not follow from the interpretation of Nat-types are externalized at the meta-level

Couldn't do this before [Johann and Polonsky 2019] because we didn't know before that nested types (and then some) always have well-defined interpretations in locally finitely presentable

categories like Set and Rel . In fact, could extend results here to “locally presentable fibrations”, where these are yet to be defined, but would at least have locally presentable base and total categories with the locally presentable structure preserved by the fibration and appropriate reflection of the total category in the base (as in Alex’s effects paper?).

Compare with Bob’s paper. What’s new?

mention Pitts categorical/denotational vs. operational semantics

Mention that we don’t have full polymorphism but just one level of forall, but most free theorems only use that anyway (even short cut). We do have fixpoints at the term level, though — even h-o ones.

It’s the ADTs that make free theorems interesting. Pitts considered lists in parpo . I extended Pitts’ to all polynomial such types.

1.1 Preliminaries

We begin with some categorical preliminaries. For a more detailed treatment of definitions and conventions the reader is referred to [].

We write Set for the category of sets and functions.

DEFINITION 1. *The category Rel is defined as follows.*

- An object of Rel is a triple (A, B, R) where R is a relation between the objects A and B in Set , i.e., a subset of $A \times B$. We write $R : \text{Rel}(A, B)$ when convenient.
- A morphism between objects $R : \text{Rel}(A, B)$ and $R' : \text{Rel}(A', B')$ of Rel is a pair $(f : A \rightarrow A', g : B \rightarrow B')$ of morphisms in Set such that $(f a, g b) \in R'$ whenever $(a, b) \in R$.

If $R : \text{Rel}(A, B)$ we write $\pi_1 R$ and $\pi_2 R$ for the domain A of R and the codomain B of R , respectively. If $A : \text{Set}$, then we write $\text{Eq}_A = (A, A, \{(x, x) \mid x \in A\})$ for the equality relation on A .

If \mathcal{C} and \mathcal{D} are categories, we write $[\mathcal{C}, \mathcal{D}]$ for the set of ω -cocontinuous functors from \mathcal{C} to \mathcal{D} .

2 THE CALCULUS

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2.1 Types

For each $k \geq 0$, we assume countable sets \mathbb{T}^k of type constructor variables of arity k , \mathbb{F}^k of functorial variables of arity k , disjoint for distinct k and disjoint from each other. We use lower case Greek letters for both sets of variables, and write ϕ^k to indicate that $\phi \in \mathbb{T}^k \cup \mathbb{F}^k$. When convenient we may write α, β , etc., rather than α^0, β^0 , etc., for elements of $\mathbb{T}^0 \cup \mathbb{F}^0$. The sets of all type constructor variables and functorial variables are $\mathbb{T} = \bigcup_{k \geq 0} \mathbb{T}^k$ and $\mathbb{F} = \bigcup_{k \geq 0} \mathbb{F}^k$, respectively, and a type variable is any element of $\mathbb{T} \cup \mathbb{F}$. We write $\bar{\zeta}$ for either a set $\{\zeta_1, \dots, \zeta_n\}$ of type constructor variables or a set of functorial variables when the cardinality n of the set is unimportant. If P is a set of type variables then we write $P, \bar{\phi}$ for $P \cup \bar{\phi}$ when $P \cap \bar{\phi} = \emptyset$. We omit the vector notation for a singleton set, thus writing ϕ , instead of $\bar{\phi}$, for $\{\phi\}$.

DEFINITION 2. *Let V be a finite subset of \mathbb{T} , let P be a finite subset of \mathbb{F} , let $\bar{\alpha}$ be a finite subset of \mathbb{F}^0 disjoint from P , and let $\phi^k \in \mathbb{F}^k \setminus P$. The sets $\mathcal{T}(V)$ of type constructor expressions over V and $\mathcal{F}^P(V)$ of functorial expressions over P and V are given by*

$$\mathcal{T}(V) ::= V \mid \text{Nat}^{\bar{\alpha}} \mathcal{F}^{\bar{\alpha}}(V) \mathcal{F}^{\bar{\alpha}}(V) \mid V \overline{\mathcal{T}}(V)$$

and

$$\begin{aligned} \mathcal{F}^P(V) ::= & \mathcal{T}(V) \mid \mathbb{0} \mid \mathbb{1} \mid \overline{P\mathcal{F}^P(V)} \mid \overline{V\mathcal{F}^P(V)} \mid \mathcal{F}^P(V) + \mathcal{F}^P(V) \mid \mathcal{F}^P(V) \times \mathcal{F}^P(V) \\ & \mid \left(\mu\phi^k . \lambda\alpha_1 \dots \alpha_k . \mathcal{F}^{P, \alpha_1, \dots, \alpha_k, \phi}(V) \right) \overline{\mathcal{F}^P(V)} \end{aligned}$$

A *type* over P and V is any element of $\mathcal{T}(V) \cup \mathcal{F}^P(V)$.

The notation for types entails that an application $\tau\tau_1 \dots \tau_k$ is allowed only when τ is a type variable of arity k , or τ is a subexpression of the form $\mu\phi^k . \lambda\alpha_1 \dots \alpha_k . \tau'$. Moreover, if τ has arity k then τ must be applied to exactly k arguments. Accordingly, an overbar indicates a sequence of subexpressions whose length matches the arity of the type applied to it. The fact that types are always in *η -long normal form* avoids having to consider β -conversion at the level of type constructors.

In a subexpression $\text{Nat}^{\bar{\alpha}} \sigma \tau$, the Nat operator binds all occurrences of the variables in $\bar{\alpha}$ in σ and τ . Similarly, in a subexpression $\mu\phi^k . \lambda\bar{\alpha} . \tau$, the μ operator binds all occurrences of the variable ϕ , and the λ operator binds all occurrences of the variables in $\bar{\alpha}$, in the body τ .

A *type constructor context* is a finite set Γ of type constructor variables, and a *functorial context* is a finite set Φ of functorial variables. In Definition 3, a judgment of the form $\Gamma; \Phi \vdash \tau : \mathcal{T}$ or $\Gamma; \Phi \vdash \tau : \mathcal{F}$ indicates that the type τ is intended to be non-functorial in the variables in Γ and functorial in the variables in Φ .

DEFINITION 3. *The formation rules for the set $\mathcal{T} \subseteq \bigcup_{V \subseteq \mathbb{T}} \mathcal{T}(V)$ of well-formed type constructor expressions are*

$$\frac{}{\Gamma, v^0; \emptyset \vdash v^0 : \mathcal{T}} \quad \frac{\Gamma; \bar{\alpha} \vdash \sigma : \mathcal{F} \quad \Gamma; \bar{\alpha} \vdash \tau : \mathcal{F}}{\Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} \sigma \tau : \mathcal{T}}$$

The formation rules for the set $\mathcal{F} \subseteq \bigcup_{V \subseteq \mathbb{T}, P \subseteq \mathbb{F}} \mathcal{F}^P(V)$ of well-formed functorial expressions are

$$\begin{aligned} & \frac{\Gamma; \emptyset \vdash \tau : \mathcal{T}}{\Gamma; \emptyset \vdash \tau : \mathcal{F}} \quad \frac{}{\Gamma; \Phi, v^0 \vdash v^0 : \mathcal{F}} \quad \frac{}{\Gamma; \Phi \vdash \mathbb{0} : \mathcal{F}} \quad \frac{}{\Gamma; \Phi \vdash \mathbb{1} : \mathcal{F}} \\ & \frac{\phi^k \in \Gamma \cup \Phi \quad \overline{\Gamma; \Phi \vdash \tau : \mathcal{F}}}{\Gamma; \Phi \vdash \phi^k \bar{\tau} : \mathcal{F}} \\ & \frac{\Gamma; \Phi, \bar{\alpha}, \phi^k \vdash \tau : \mathcal{F} \quad \overline{\Gamma; \Phi \vdash \tau : \mathcal{F}}}{\Gamma; \Phi \vdash (\mu\phi^k . \lambda\bar{\alpha} . \tau) \bar{\tau} : \mathcal{F}} \\ & \frac{\Gamma; \Phi \vdash \sigma : \mathcal{F} \quad \Gamma; \Phi \vdash \tau : \mathcal{F}}{\Gamma; \Phi \vdash \sigma + \tau : \mathcal{F}} \quad \frac{\Gamma; \Phi \vdash \sigma : \mathcal{F} \quad \Gamma; \Phi \vdash \tau : \mathcal{F}}{\Gamma; \Phi \vdash \sigma \times \tau : \mathcal{F}} \end{aligned}$$

A *type* τ is well-formed if it is either a well-formed type constructor expression or a well-formed functorial expression.

Include some examples of types, e.g., lists and perfect trees and bushes, etc. Include those that will be used in discussions below.

Note that we cannot write as folds functions — such as `concat :: PTree a -> PTree a -> PTree a` — that take as input more than one non-algebraic nested type. This is because the restriction on the contexts in which Nat -types can be formed conflicts with the need to feed folds algebras. (Can't fold over pairs to get the right functions; can't get them by using continuation style because of the aforementioned typing conflict.)

If τ is a closed type we may write $\vdash \tau$, rather than $\emptyset; \emptyset \vdash \tau$, for the judgment that it is well-formed. Definition 3 ensures that the expected weakening rules for well-formed types hold. (Note, however, that weakening does not change the contexts in which Nat-types can be formed.) If $\Gamma; \emptyset \vdash \sigma : \mathcal{T}$ and $\Gamma; \emptyset \vdash \tau : \mathcal{T}$, then our rules allow formation of the type $\Gamma; \emptyset \vdash \text{Nat}^0 \sigma \tau$. This type can be thought of as representing the standard arrow type $\Gamma \vdash \sigma \rightarrow \tau$ in our calculus. We can similarly represent a standard \forall -type $\Gamma; \emptyset \vdash \forall \bar{\alpha}. \tau$ as the well-formed type $\Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} \mathbb{1} \tau : \mathcal{F}$. However, if $\bar{\alpha}$ is non-empty then τ cannot be of the form $\text{Nat}^{\bar{\beta}} H K$; indeed, $\Gamma; \bar{\alpha} \vdash \text{Nat}^{\bar{\beta}} H K$ is an invalid typing judgment in our calculus (except by weakening).

Our formation rules also allow a type like $\text{List } \gamma = (\mu\beta. \lambda\alpha. \mathbb{1} + \alpha \times \beta)\gamma$ either to be natural in γ or not, according to whether it is well-formed in the context $\emptyset; \gamma$ or $\gamma; \emptyset$. If the former, then the type $\vdash \text{Nat}^{\gamma} \mathbb{1} (\text{List } \gamma) : \mathcal{T}$ is well-formed; if the latter, then it is not. Our formation rules also allow the derivation of, e.g., $\delta; \emptyset \vdash \text{Nat}^{\gamma} (\text{List } \gamma) (\text{Tree } \gamma \delta)$, which represents a natural transformation between lists and trees that is natural in γ but not in δ . We explicitly note that types can be functorial in variables of arity greater than 0. For example, the type $\text{GRose } \phi \alpha = \mu\beta. \alpha \times \phi\beta$ can be functorial in ϕ or not according to whether $\phi \in \Gamma$ or $\phi \in \Phi$. This choice of context for ϕ determines whether types such as $\text{Nat}^{\alpha} (\text{GRose } \phi \alpha) (\text{List } \alpha)$ are well-formed. If GRose is functorial in ϕ , i.e. if $\emptyset; \alpha, \phi \vdash \mu\beta. \alpha \times \phi\beta$, then GRose cannot be used as a (co)domain in Nat types. This is because our calculus does not allow naturality in variables of arity greater than 0.

2.2 A Demotion Theorem

[Move statement of theorem earlier?](#) There is a subtlety in the well-formedness rules for types.

THEOREM 4. *If $\Gamma; \Phi, \phi^k \vdash \tau : \mathcal{F}$, then one can derive $\Gamma, \psi^k; \Phi \vdash \tau[\phi^k := \psi^k]$, where $\tau[\phi := \psi]$ is the textual replacement of ϕ in τ . In other words, all occurrences of $\phi\bar{\sigma}$ in τ become $\psi\bar{\sigma}$.*

PROOF. By induction on the structure of τ .

- Case $\Gamma; \Phi, \alpha \vdash \alpha : \mathcal{F}$. We must derive $\Gamma, \beta; \Phi \vdash \beta : \mathcal{F}$.

$$\frac{\Gamma, \beta; \emptyset \vdash \beta : \mathcal{T}}{\Gamma, \beta; \emptyset \vdash \beta : \mathcal{F}} \\ \frac{\Gamma, \beta; \emptyset \vdash \beta : \mathcal{F}}{\Gamma, \beta; \Phi \vdash \beta : \mathcal{F}}$$

- Case $\Gamma; \Phi, \phi \vdash \phi\bar{\tau} : \mathcal{F}$. We must derive $\Gamma, \psi; \Phi \vdash (\phi\bar{\tau})[\phi := \psi] : \mathcal{F}$. The induction hypothesis gives that $\Gamma, \psi; \Phi \vdash \tau[\phi := \psi] : \mathcal{F}$ for each τ .

$$\frac{\psi \in \{\Gamma, \psi\} \cup \Phi : \mathcal{F} \quad \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] : \mathcal{F}}{\Gamma, \psi; \Phi \vdash \psi\tau[\phi := \psi] : \mathcal{F}} \\ \frac{\Gamma, \psi; \Phi \vdash \psi\tau[\phi := \psi] : \mathcal{F}}{\Gamma, \psi; \Phi \vdash (\phi\bar{\tau})[\phi := \psi] : \mathcal{F}}$$

The case for $\Gamma; \Phi, \phi' \vdash \phi'\bar{\tau} : \mathcal{F}$, i.e., the case in which the variable being “demoted” only appears in the arguments, works by the same induction.

- Case $\Gamma; \Phi, \phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H)\bar{\tau} : \mathcal{F}$. We must derive $\Gamma, \psi; \Phi \vdash ((\mu\phi'. \lambda\bar{\alpha}. H)\bar{\tau})[\phi := \psi] : \mathcal{F}$. The induction hypothesis gives that $\Gamma, \psi; \Phi \vdash \tau[\phi := \psi] : \mathcal{F}$ for each τ and $\Gamma, \psi; \Phi, \bar{\alpha}, \phi' \vdash H[\phi := \psi] : \mathcal{F}$.

$$\frac{\Gamma, \psi; \Phi, \bar{\alpha}, \phi' \vdash H[\phi := \psi] : \mathcal{F} \quad \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] : \mathcal{F}}{\Gamma, \psi; \Phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H[\phi := \psi])\tau[\phi := \psi] : \mathcal{F}} \\ \frac{\Gamma, \psi; \Phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H[\phi := \psi])\tau[\phi := \psi] : \mathcal{F}}{\Gamma, \psi; \Phi \vdash ((\mu\phi'. \lambda\bar{\alpha}. H)\bar{\tau})[\phi := \psi] : \mathcal{F}}$$

□

The next two theorems are proven by simultaneous induction. We are actually only interested in using Theorem 5, but in order to prove the μ case for this theorem, we need Theorem ?? to show that two functors have equal actions on morphisms.

THEOREM 5. *Let $\Gamma; \Phi, \phi \vdash \tau : \mathcal{F}$. If $\rho, \rho' : \text{SetEnv}$ are such that $\rho\phi = \rho\psi = \rho'\phi = \rho'\psi$, and if $f : \rho \rightarrow \rho'$ is a morphism of set environments such that $f\phi = f\psi = \text{id}_{\rho\phi}$, then*

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho$$

and

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} f = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f$$

Analogously, if $\rho, \rho' : \text{RelEnv}$ are such that $\rho\phi = \rho\psi = \rho'\phi = \rho'\psi$, and if $f : \rho \rightarrow \rho'$ is a morphism of relation environments such that $f\phi = f\psi = \text{id}_{\rho\phi}$, then

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Rel}} \rho = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Rel}} \rho$$

and

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Rel}} f = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Rel}} f$$

PROOF. We prove the result for set interpretations by induction on the structure of τ . The case for relational interpretations proceeds analogously. Since the only interesting cases are the application case and the μ -case, we elide the others.

- If $\Gamma; \Phi, \phi \vdash \phi\bar{\tau} : \mathcal{F}$, then the induction hypothesis gives that

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho$$

and

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} f = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f$$

for each τ . Then

$$\begin{aligned} & \llbracket \Gamma; \Phi, \phi \vdash \phi\bar{\tau} \rrbracket^{\text{Set}} \rho \\ &= (\rho\phi) \overline{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho} \\ &= (\rho\phi) \overline{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho} \\ &= (\rho\psi) \overline{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho} \\ &= \llbracket \Gamma, \psi; \Phi \vdash \psi\tau[\phi := \psi] \rrbracket^{\text{Set}} \rho \\ &= \llbracket \Gamma, \psi; \Phi \vdash (\phi\bar{\tau})[\phi := \psi] \rrbracket^{\text{Set}} \rho \end{aligned}$$

Here, the first and fifth equalities are by Definition 10, and the fourth equality is by equality of the functors $\rho\phi$ and $\rho\psi$. We also have that

$$\begin{aligned}
 & \llbracket \Gamma; \Phi, \phi \vdash \phi\bar{\tau} \rrbracket^{\text{Set}} f \\
 &= (f\phi)_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho'} \circ (\rho\phi)_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} f} \\
 &= (id_{\rho\phi})_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho'} \circ (\rho\phi)_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} f} \\
 &= (\rho\phi)_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} f} \\
 &= (\rho\psi)_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f} \\
 &= (id_{\rho\psi})_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho'} \circ (\rho\psi)_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f} \\
 &= (f\psi)_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho'} \circ (\rho\psi)_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f} \\
 &= \llbracket \Gamma, \psi; \Phi \vdash \psi\tau[\phi := \psi] \rrbracket^{\text{Set}} f \\
 &= \llbracket \Gamma, \psi; \Phi \vdash (\phi\bar{\tau})[\phi := \psi] \rrbracket^{\text{Set}} f
 \end{aligned}$$

- If $\Gamma; \Phi, \phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H)\bar{\tau} : \mathcal{F}$, then the induction hypothesis gives that

$$\llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho = \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} \rho$$

and

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho$$

as well as that

$$\llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} f = \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} f$$

and

$$\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} f = \llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f$$

for each τ . Then

$$\begin{aligned}
 & \llbracket \Gamma; \Phi, \phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H)\bar{\tau} \rrbracket^{\text{Set}} \rho \\
 &= (\mu(\lambda F. \lambda\bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := \bar{A}]))_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho} \\
 &= (\mu(\lambda F. \lambda\bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := \bar{A}]))_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho} \\
 &= (\mu(\lambda F. \lambda\bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := \bar{A}]))_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho} \\
 &= \llbracket \Gamma, \psi; \Phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H[\phi := \psi])\tau[\phi := \psi] \rrbracket^{\text{Set}} \rho \\
 &= \llbracket \Gamma, \psi; \Phi \vdash ((\mu\phi'. \lambda\bar{\alpha}. H)\bar{\tau})[\phi := \psi] \rrbracket^{\text{Set}} \rho
 \end{aligned}$$

The first and fifth equalities are by Definition 10. The second equality follows from the following equality:

$$\begin{aligned}
 & \lambda F. \lambda\bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := \bar{A}] \\
 &= \lambda F. \lambda\bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := \bar{A}]
 \end{aligned}$$

These two maps have the same actions on objects and morphisms by the induction hypothesis on H , and the fact that the extended environment $\rho[\phi' := F][\bar{\alpha} := \bar{A}]$ satisfies the required

hypothesis. They are thus equal as functors and so have the same fixed point. We also have that

$$\begin{aligned}
& \llbracket \Gamma; \Phi, \phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Set}} f \\
&= (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} f[\phi' := id_F][\bar{\alpha} := id_A]))_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho'} \\
&\quad \circ (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := A]))_{\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} f} \\
&= (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} f[\phi' := id_F][\bar{\alpha} := id_A]))_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho'} \\
&\quad \circ (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := A]))_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f} \\
&= (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} f[\phi' := id_F][\bar{\alpha} := id_A]))_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho'} \\
&\quad \circ (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := A]))_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f} \\
&= (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} f[\phi' := id_F][\bar{\alpha} := id_A]))_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} \rho'} \\
&\quad \circ (\mu(\lambda F. \lambda \bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := A]))_{\llbracket \Gamma, \psi; \Phi \vdash \tau[\phi := \psi] \rrbracket^{\text{Set}} f} \\
&= \llbracket \Gamma, \psi; \Phi \vdash (\mu\phi'. \lambda\bar{\alpha}. H[\phi := \psi]) \bar{\tau}[\phi := \psi] \rrbracket^{\text{Set}} f \\
&= \llbracket \Gamma, \psi; \Phi \vdash ((\mu\phi'. \lambda\bar{\alpha}. H) \bar{\tau})[\phi := \psi] \rrbracket^{\text{Set}} f
\end{aligned}$$

The first and fifth equalities are by Definition 10. The third equality is by the equality of the arguments to the first μ operator:

$$\begin{aligned}
& \lambda F. \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} f[\phi' := id_F][\bar{\alpha} := id_A] \\
&= \lambda F. \lambda \bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} f[\phi' := id_F][\bar{\alpha} := id_A]
\end{aligned}$$

By the induction hypothesis on H and the fact that the morphism $f[\phi' := id_F][\bar{\alpha} := id_A] : \rho[\phi' := F][\bar{\alpha} := A] \rightarrow \rho'[\phi' := F][\bar{\alpha} := A]$ still satisfies the required hypotheses. The fourth equality is by the equality of the arguments to the second μ operator:

$$\begin{aligned}
& \lambda F. \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi', \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := A] \\
&= \lambda F. \lambda \bar{A}. \llbracket \Gamma, \psi; \Phi, \phi', \bar{\alpha} \vdash H[\phi := \psi] \rrbracket^{\text{Set}} \rho[\phi' := F][\bar{\alpha} := A]
\end{aligned}$$

By the same reasoning as above, these two maps are equal as functors, and thus have the same fixed point. \square

2.3 Substitution for Types

If τ is a type, P and V contain only type variables of arity 0, and $k = 0$ for every occurrence of ϕ^k bound by μ in τ , then we say that τ is *first-order*. Otherwise we say that τ is *second-order*. Substitution for first-order types is the usual capture-avoiding textual substitution. We write $\tau[\alpha := \sigma]$ for the result of substituting σ for α in τ , and $\tau[\alpha_1 := \tau_1, \dots, \alpha_k := \tau_k]$, or $\tau[\bar{\alpha} := \bar{\tau}]$ when convenient, for $\tau[\alpha_1 := \tau_1][\alpha_2 := \tau_2, \dots, \alpha_k := \tau_k]$. Substitution for second-order types is defined as follows.

DEFINITION 6. If $\Gamma; \Phi \vdash F[\phi] : \mathcal{F}$, $\phi^k \in \Gamma \cup \Phi$, $k \geq 1$, and $\Gamma, \bar{\beta}; \Phi, \bar{\alpha} \vdash H : \mathcal{F}$ with $|\bar{\alpha}| + |\bar{\beta}| = k$, then $\Gamma \setminus \phi^k; \Phi \setminus \phi^k \vdash F[\phi := \bar{\beta}, \bar{\alpha} H] : \mathcal{F}$. The operation $(\cdot)[\phi := H]$ of second-order type substitution

is defined by:

$$\begin{aligned}
(\text{Nat}^{\bar{\gamma}} G K)[\phi :=_{\bar{\beta}, \bar{\alpha}} H] &= \text{Nat}^{\bar{\gamma}} G[\phi :=_{\bar{\beta}, \bar{\alpha}} H] K[\phi :=_{\bar{\beta}, \bar{\alpha}} H] \\
\mathbb{1}[\phi :=_{\bar{\beta}, \bar{\alpha}} H] &= \mathbb{1} \\
\mathbb{0}[\phi :=_{\bar{\beta}, \bar{\alpha}} H] &= \mathbb{0} \\
(\psi \overline{\sigma \tau})[\phi :=_{\bar{\beta}, \bar{\alpha}} H] &= \begin{cases} \psi \overline{\tau[\phi :=_{\bar{\beta}, \bar{\alpha}} H]} & \text{if } \psi \neq \phi \\ H[\alpha := \tau[\phi :=_{\bar{\beta}, \bar{\alpha}} H]][\beta := \sigma[\phi :=_{\bar{\beta}, \bar{\alpha}} H]] & \text{if } \psi = \phi \end{cases} \\
(\sigma + \tau)[\phi :=_{\bar{\beta}, \bar{\alpha}} H] &= \sigma[\phi :=_{\bar{\beta}, \bar{\alpha}} H] + \tau[\phi :=_{\bar{\beta}, \bar{\alpha}} H] \\
(\sigma \times \tau)[\phi :=_{\bar{\beta}, \bar{\alpha}} H] &= \sigma[\phi :=_{\bar{\beta}, \bar{\alpha}} H] \times \tau[\phi :=_{\bar{\beta}, \bar{\alpha}} H] \\
((\mu\psi.\lambda\bar{\gamma}. G)\bar{\tau})[\phi :=_{\bar{\beta}, \bar{\alpha}} H] &= (\mu\psi.\lambda\bar{\gamma}. G[\phi :=_{\bar{\beta}, \bar{\alpha}} H]) \tau[\phi :=_{\bar{\beta}, \bar{\alpha}} H]
\end{aligned}$$

We omit the variable subscripts in second-order type constructor substitution when clear from context or otherwise convenient.

2.4 Terms

We assume an infinite set \mathcal{V} of term variables disjoint from \mathbb{T} and \mathbb{F} .

DEFINITION 7. Let Γ be a type constructor context and Φ be a functorial context. A term context for Γ and Φ is a finite set of bindings of the form $x : \tau$, where $x \in \mathcal{V}$ and $\Gamma; \Phi \vdash \tau : \mathcal{F}$.

We adopt the same conventions for denoting disjoint unions in term contexts as for type constructor contexts and functorial contexts.

DEFINITION 8. Let Δ be a term context for Γ and Φ . The formation rules for the set of well-formed terms over Δ are

$$\begin{array}{c}
\frac{\Gamma; \emptyset \vdash \tau : \mathcal{T}}{\Gamma; \emptyset \mid \Delta, x : \tau \vdash x : \tau} \quad \frac{\Gamma; \Phi \vdash \tau : \mathcal{F}}{\Gamma; \Phi \mid \Delta, x : \tau \vdash x : \tau} \\
\frac{}{\Gamma; \Phi \mid \Delta \vdash \top : \mathbb{1}} \quad \frac{\Gamma; \Phi \mid \Delta \vdash t : \mathbb{0} \quad \Gamma; \Phi \vdash \tau : \mathcal{F}}{\Gamma; \Phi \mid \Delta \vdash \perp_{\tau} t : \tau} \\
\frac{}{\Gamma; \Phi \mid \Delta \vdash s : \sigma} \quad \frac{}{\Gamma; \Phi \mid \Delta \vdash t : \tau} \\
\frac{}{\Gamma; \Phi \mid \Delta \vdash \text{inl } s : \sigma + \tau} \quad \frac{}{\Gamma; \Phi \mid \Delta \vdash \text{inr } t : \sigma + \tau} \\
\frac{\Gamma; \Phi \vdash \tau, \sigma : \mathcal{F} \quad \Gamma; \Phi \mid \Delta \vdash t : \sigma + \tau \quad \Gamma; \Phi \mid \Delta, x : \sigma \vdash l : \gamma \quad \Gamma; \Phi \mid \Delta, y : \tau \vdash r : \gamma}{\Gamma; \Phi \mid \Delta \vdash \text{case } t \text{ of } \{\text{inl } x \mapsto l; \text{inr } y \mapsto r\} : \gamma} \\
\frac{\Gamma; \Phi \mid \Delta \vdash s : \sigma \quad \Gamma; \Phi \mid \Delta \vdash t : \tau}{\Gamma; \Phi \mid \Delta \vdash (s, t) : \sigma \times \tau} \quad \frac{\Gamma; \Phi \mid \Delta \vdash t : \sigma \times \tau}{\Gamma; \Phi \mid \Delta \vdash \pi_1 t : \sigma} \quad \frac{\Gamma; \Phi \mid \Delta \vdash t : \sigma \times \tau}{\Gamma; \Phi \mid \Delta \vdash \pi_2 t : \tau}
\end{array}$$

$$\begin{array}{c}
\frac{\Gamma; \bar{\alpha} \vdash F : \mathcal{F} \quad \Gamma; \bar{\alpha} \vdash G : \mathcal{F} \quad \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G}{\Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x. t : \text{Nat}^{\bar{\alpha}} F G} \\
\\
\frac{\Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \quad \overline{\Gamma; \Phi \vdash \tau : \mathcal{F}} \quad \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \tau]}{\Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \tau]} \\
\\
\frac{\Gamma; \bar{\phi}, \bar{\gamma} \vdash H : \mathcal{F} \quad \overline{\Gamma; \bar{\beta}, \bar{\gamma} \vdash F : \mathcal{F}} \quad \overline{\Gamma; \bar{\beta}, \bar{\gamma} \vdash G : \mathcal{F}}}{\Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\bar{H}}^{\bar{F}, \bar{G}} : \text{Nat}^{\emptyset} (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}])} \\
\\
\frac{\Gamma; \bar{\phi}, \bar{\alpha}, \bar{\gamma} \vdash H : \mathcal{F}}{\Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} (\mu\phi. \lambda\bar{\alpha}. H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi. \lambda\bar{\alpha}. H)\bar{\beta}} \\
\\
\frac{\Gamma; \bar{\phi}, \bar{\alpha}, \bar{\gamma} \vdash H : \mathcal{F} \quad \Gamma; \bar{\beta}, \bar{\gamma} \vdash F : \mathcal{F}}{\Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^{\emptyset} (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda\bar{\alpha}. H)\bar{\beta}) \bar{F}}
\end{array}$$

In the rule for $L_{\bar{\alpha}} x. t$, the L operator binds all occurrences of the type variables in $\bar{\alpha}$ in the type of the term variable x and in the body t , as well as all occurrences of x in t . In the rule for $t_{\bar{\tau}} s$ there is one functorial expression τ for every functorial variable α . In the rule for $\text{map}_{\bar{H}}^{\bar{F}, \bar{G}}$ there is one functorial expression F and one functorial expression G for each functorial variable in $\bar{\phi}$. Moreover, for each $\phi^k \in \bar{\phi}$ the number of functorial variables β in the judgments for its corresponding functorial expressions F and G is k . In the rules for in_H and fold_H^F , the functorial variables in $\bar{\beta}$ are fresh with respect to H , and there is one β for every α . (Recall from above that, in order for the types of in_H and fold_H^F to be well-formed, the number of α s must equal the arity of ϕ .)

Substitution for terms is the obvious extension of the usual capture-avoiding textual substitution. Definition 8 ensures that the expected weakening rules for well-formed terms hold.

Let PLeaves be the type $\emptyset; \beta \vdash (\mu\phi. \lambda\alpha. \alpha + \phi(\alpha \times \alpha))\beta$. We will define a reverse function with type $\vdash \text{reverse} : \text{Nat}^{\beta}(\text{PLeaves } \beta) (\text{PLeaves } \beta)$.

To begin with, define the term swap as

$$\vdash L_{\beta} p. (\pi_2 p, \pi_1 p) : \text{Nat}^{\beta}(\beta \times \beta) (\beta \times \beta)$$

and consider the map for PLeaves

$$\vdash \text{map}_{\text{PLeaves } \beta}^{\beta \times \beta, \beta \times \beta} : \text{Nat}^{\emptyset}(\text{Nat}^{\beta}(\beta \times \beta) (\beta \times \beta)) (\text{Nat}^{\beta}(\text{PLeaves } (\beta \times \beta)) (\text{PLeaves } (\beta \times \beta)))$$

Then we get a term

$$\vdash \text{map}_{\text{PLeaves } \beta}^{\beta \times \beta, \beta \times \beta} \text{ swap} : \text{Nat}^{\beta}(\text{PLeaves } (\beta \times \beta)) (\text{PLeaves } (\beta \times \beta))$$

Define the term s as

$$\begin{aligned}
&\vdash L_{\beta} t. \text{case } t \text{ of } \{b \mapsto \text{inl } b; t' \mapsto \text{inr}(\text{map}_{\text{PLeaves } \beta}^{\beta \times \beta, \beta \times \beta} \text{ swap } t')\} \\
&\quad : \text{Nat}^{\beta}(\beta + \text{PLeaves } (\beta \times \beta)) (\beta + \text{PLeaves } (\beta \times \beta))
\end{aligned}$$

and consider the mediating morphism in of the initial algebra defining PLeaves

$$\vdash \text{in}_{\alpha + \phi(\alpha \times \alpha)} : \text{Nat}^{\beta}(\beta + \text{PLeaves } (\beta \times \beta)) (\text{PLeaves } \beta)$$

Then we get a term

$$\vdash \text{in}_{\alpha+\phi(\alpha \times \alpha)} \circ s : \text{Nat}^\beta(\beta + \text{PLeaves}(\beta \times \beta)) (\text{PLeaves} \beta)$$

Finally, consider the fold for PLeaves

$$\vdash \text{fold}_{\alpha+\phi(\alpha \times \alpha)}^{\text{PLeaves} \beta} : \text{Nat}^0(\text{Nat}^\beta(\beta + \text{PLeaves}(\beta \times \beta)) (\text{PLeaves} \beta)) (\text{Nat}^\beta(\text{PLeaves} \beta) (\text{PLeaves} \beta))$$

then we define the reverse function as

$$\vdash \text{fold}_{\alpha+\phi(\alpha \times \alpha)}^{\text{PLeaves} \beta} (\text{in}_{\alpha+\phi(\alpha \times \alpha)} \circ s) : \text{Nat}^\beta(\text{PLeaves} \beta) (\text{PLeaves} \beta)$$

The presence of the “extra” functorial variables in $\bar{\gamma}$ in the rules for $\text{map}_H^{\bar{F}, \bar{G}}$, in_H , and fold_H^F merit special mention. It allows us to, e.g., map or fold polymorphic functions over data types. For example, consider the function $\text{flatten} : \text{Nat}^\beta(\text{PTree} \beta) (\text{List} \beta)$ that maps perfect trees to lists. Even without the “extra” γ s the term representing the mapping of each *instance* of flatten acting on perfect trees and lists of types involving no functorial variables is well-typed:

$$\frac{\Gamma; \alpha \vdash \text{List } \alpha \quad \Gamma; \emptyset \vdash \sigma \quad \Gamma; \emptyset \vdash \tau \quad \Gamma; \emptyset \vdash \text{PTree } \sigma \quad \Gamma; \emptyset \vdash \text{List } \tau}{\Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\text{List}}^{F, G} : \text{Nat}^0(\text{Nat}^0(\text{PTree } \sigma) (\text{List } \tau)) (\text{Nat}^0(\text{List} (\text{PTree } \sigma)) (\text{List} (\text{List } \tau)))}$$

But because the functorial contexts for the expressions instantiating F and G in the rule for $\text{map}_H^{F, G}$ are necessarily empty, the term representing the mapping of the polymorphic function flatten is not. Indeed, the polymorphic function flatten , whose type contains the functorial variable β , say, cannot have a type of the form $\text{Nat}^0 F' G'$ for any F' and G' as is required in the conclusion of the rule for $\text{map}_{\text{List}}^{F, G}$. However, in a polymorphic calculus of course we want to be able to manipulate terms representing polymorphic functions in their entirety rather than just their monomorphic instantiations. The rules with the “extra” γ s recover this capability. For example, with these rules the term representing the mapping of polymorphic flatten is typeable as follows:

$$\frac{\Gamma; \alpha, \beta \vdash \text{List } \alpha \quad \Gamma; \beta \vdash \text{PTree } \beta \quad \Gamma; \beta \vdash \text{List } \beta}{\Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\text{List}}^{F, G} : \text{Nat}^0(\text{Nat}^\beta(\text{PTree } \beta) (\text{List } \beta)) (\text{Nat}^\beta(\text{List} (\text{PTree } \beta)) (\text{List} (\text{List } \beta)))}$$

3 INTERPRETING TYPES

The key idea underlying parametricity is to give each type $T(\alpha)$ with a free type variable α both an *object interpretation* T_0 taking sets to sets and a *relational interpretation* T_1 taking relations $R \subseteq A \times B$ to relations $T_1(R) \subseteq T_0(A) \times T_0(B)$, and to interpret each term $\alpha \mid x : S(\alpha) \vdash t(\alpha, x) : T(\alpha)$ as a map t_0 associating to each set A a function $t_0(A) : S_0(A) \rightarrow T_0(A)$. These interpretations were to be given inductively on the structure of T and t in such a way that they imply two key theorems: an *Identity Extension Lemma*, stating that if R is the equality relation on A then $T_1(R)$ is the equality relation on $T_0(A)$; and an *Abstraction Theorem*, stating that, for any relation $R \subseteq A \times B$, $t_0(A)$ and $t_0(B)$ map arguments related by $S_1(R)$ to results related by $T_1(R)$. Similar results hold for types and terms with any number of free variables.

Free theorems are just instantiations of the Abstraction Theorem.

Parametricity requires that set interpretations of types are defined simultaneously with their relational interpretations. This is because the underlying interpretations of Nat types must be cut down to include only the “parametric” elements, as discussed in, e.g., [Reynolds 1983; ?; ?]. Indeed, without this cutting down it will not be possible to prove the Identity Extension Lemma (Theorem 31), which is the key property that makes a model relationally parametric, rather than just induced by a logical relation. The Identity Extension Lemma is similar to the Abstraction Theorem (Theorem 37), except that it applies to *all* elements of a type’s interpretation, not just

those that are interpretations of terms. It can therefore be used to reason about arbitrary elements of a type's interpretation, not just those that are interpretations of terms.

In this section we give the set interpretations for types; in the next section we give their relational interpretations. While the set interpretations are relatively straightforward, their relation interpretations are less so, mainly because of the cocontinuity conditions we must impose to ensure that they are well-behaved. We take some effort to develop these in Section 3.2, which separates Definitions 10 and 21 in space, but otherwise has no impact on the fact that they are given by mutual induction.

3.1 Interpreting Types as Sets

To ensure that we stay in the setting of [Johann and Polonsky 2019] — and thus to ensure that all of the types in our calculus have well-defined interpretations in Set and Rel — we interpret all type variables as ω -cocontinuous functors in Definitions 9 and 19.

DEFINITION 9. *A set environment maps each type variable in $\mathbb{T}^k \cup \mathbb{F}^k$ to an element of $[\text{Set}^k, \text{Set}]$. A morphism $f : \rho \rightarrow \rho'$ from a set environment ρ to a set environment ρ' with $\rho|_{\mathbb{T}} = \rho'|_{\mathbb{T}}$ maps each type constructor variable $\psi^k \in \mathbb{T}$ to the identity natural transformation on $\rho\psi^k = \rho'\psi^k$ and maps each functorial variable $\phi^k \in \mathbb{F}$ to a natural transformation from the k -ary functor $\rho\phi^k$ on Set to the k -ary functor $\rho'\phi^k$ on Set. Composition of morphisms on set environments is given componentwise, with the identity morphism mapping each set environment to itself. This gives a category of set environments and morphisms between them, which we denote SetEnv .*

When convenient we identify a functor $F : [\text{Set}^0, \text{Set}]$ with the set that is its codomain. With this convention, a set environment maps a type variable of arity 0 to an ω -cocontinuous functor from Set^0 to Set — i.e., to a set. If $\bar{\alpha} = \{\alpha_1, \dots, \alpha_k\}$ and $\bar{A} = \{A_1, \dots, A_k\}$, then we write $\rho[\bar{\alpha} := \bar{A}]$ for the set environment ρ' such that $\rho'\alpha_i = A_i$ for $i = 1, \dots, k$ and $\rho'\alpha = \rho\alpha$ if $\alpha \notin \{\alpha_1, \dots, \alpha_k\}$.

If ρ is a set environment we write Eq_ρ for the relation environment such that $\text{Eq}_\rho v = \text{Eq}_{\rho v}$ for every type variable v ; see Definition 19 below for the complete definition of a relation environment. The relational interpretations referred to in the condition on the natural transformations in the clause of Definition 10 for types of the form $\text{Nat}^{\bar{\alpha}} FG$ are given in full in Definition 21. As usual, this condition ensures that the interpretations of such types are sufficiently uniform to ensure parametricity.

DEFINITION 10. Let ρ be a set environment. The set interpretation $\llbracket \cdot \rrbracket^{\text{Set}} : \mathcal{F} \rightarrow [\text{SetEnv}, \text{Set}]$ is defined by

$$\begin{aligned}
 \llbracket \Gamma; \emptyset \vdash v \rrbracket^{\text{Set}} \rho &= \rho v \text{ if } v \in \mathbb{T}^0 \\
 \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho &= \{ \eta : \lambda \bar{A}. \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}] \Rightarrow \lambda \bar{A}. \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}] \\
 &\quad | \forall \bar{A}, \bar{B} : \text{Set}. \forall R : \text{Rel}(\bar{A}, \bar{B}). \\
 &\quad (\eta_{\bar{A}}, \eta_{\bar{B}}) : \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho}[\bar{\alpha} := \bar{R}] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_{\rho}[\bar{\alpha} := \bar{R}] \} \\
 \llbracket \Gamma; \Phi \vdash 0 \rrbracket^{\text{Set}} \rho &= 0 \\
 \llbracket \Gamma; \Phi \vdash 1 \rrbracket^{\text{Set}} \rho &= 1 \\
 \llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Set}} \rho &= (\rho \phi) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} \\
 \llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Set}} \rho &= \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho + \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \\
 \llbracket \Gamma; \Phi \vdash \sigma \times \tau \rrbracket^{\text{Set}} \rho &= \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho \times \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \\
 \llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Set}} \rho &= (\mu T_{\rho}^{\text{Set}}) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} \\
 &\quad \text{where } T_{\rho}^{\text{Set}} F = \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\phi := F][\bar{\alpha} := \bar{A}] \\
 &\quad \text{and } T_{\rho}^{\text{Set}} \eta = \lambda \bar{A}. \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \text{id}_{\rho}[\phi := \eta][\bar{\alpha} := \text{id}_{\bar{A}}]
 \end{aligned}$$

The interpretations in Definition 10 respect weakening, i.e., a type and its weakenings all have the same set interpretations. The same holds for the actions of these interpretations on morphisms in Definition 11 below. Moreover, the interpretation of Nat types ensures that $\llbracket \Gamma \vdash \sigma \rightarrow \tau \rrbracket^{\text{Set}} \rho = \llbracket \Gamma \vdash \sigma \rrbracket^{\text{Set}} \rho \rightarrow \llbracket \Gamma \vdash \tau \rrbracket^{\text{Set}} \rho$, as expected. If ρ is a set environment and $\vdash \tau : \mathcal{F}$ then we may write $\llbracket \vdash \tau \rrbracket^{\text{Set}}$ instead of $\llbracket \vdash \tau \rrbracket^{\text{Set}} \rho$ since the environment is immaterial. We note that the second clause of Definition 10 does indeed define a set. Indeed, local finite presentability of Set and ω -cocontinuity of $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho$ ensure that $\{ \eta : \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho \Rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho \}$ (which contains $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho$) is a subset of

$$\{ (\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{S}]) (\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{S}]) \mid \bar{S} = (S_1, \dots, S_{|\bar{\alpha}|}), \text{ and } S_i \text{ is a finite set for } i = 1, \dots, |\bar{\alpha}| \}$$

There are countably many choices for tuples \bar{S} , and each of these gives rise to a morphism from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{S}]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{S}]$. But there are only Set-many choices of morphisms between these (or any) two objects because Set is locally small.

In order to make sense of the last clause in Definition 10, we need to know that, for each $\rho \in \text{SetEnv}$, T_{ρ}^{Set} is an ω -cocontinuous endofunctor on $[\text{Set}^k, \text{Set}]$, and thus admits a fixed point. Since T_{ρ}^{Set} is defined in terms of $\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}}$, this means that set interpretations of types must be ω -cocontinuous functors. This in turn means that the actions of set interpretations of types on objects and on morphisms in SetEnv are intertwined. In fact, we know from [Johann and Polonsky 2019] that, for every $\Gamma; \bar{\alpha} \vdash \tau : \mathcal{F}$, $\llbracket \Gamma; \bar{\alpha} \vdash \tau \rrbracket^{\text{Set}}$ is actually functorial in $\bar{\alpha}$ and ω -cocontinuous.

Indeed, for each $\llbracket \Gamma; \Phi, \phi^k, \bar{\alpha} \vdash H \rrbracket^{\text{Set}}$, the corresponding operator T^{Set} Should be T_H^{Set} , really, and similarly throughout. can be extended to a functor from SetEnv to $[[\text{Set}^k, \text{Set}], [\text{Set}^k, \text{Set}]]$. The action of T^{Set} on an object $\rho \in \text{SetEnv}$ is given by the higher-order functor T_{ρ}^{Set} , whose actions on objects (functors from Set^k to Set) and morphisms (natural transformations between such functors) are as defined in Definition 10. The action of T_H^{Set} on a morphism $f : \rho \rightarrow \rho'$ is the higher-order natural transformation May want to use $T_{H,f}^{\text{Set}}$ rather than σ_f^{Set} in final version. $\sigma_f^{\text{Set}} : T_{\rho}^{\text{Set}} \rightarrow T_{\rho'}^{\text{Set}}$ whose action on any $F : [\text{Set}^k, \text{Set}]$ is the natural transformation $\sigma_f^{\text{Set}} F : T_{\rho}^{\text{Set}} F \rightarrow T_{\rho'}^{\text{Set}} F$ whose

component at \bar{A} is

$$(\sigma_f^{\text{Set}} F)_{\bar{A}} = \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} f[\phi := id_F][\bar{\alpha} := id_{\bar{A}}]$$

The next definition uses this observation to define the action of each functor interpreting a type on morphisms between set environments.

DEFINITION 11. Let $f : \rho \rightarrow \rho'$ for set environments ρ and ρ' (so that $\rho|_{\mathbb{T}} = \rho'|_{\mathbb{T}}$). The action $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f$ of $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}$ on the morphism f is given as follows:

- If $\Gamma, v; \emptyset \vdash v$ then $\llbracket \Gamma, v; \emptyset \vdash v \rrbracket^{\text{Set}} f = id_{\rho v}$.
- If $\Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G$, then we define $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} f = id_{\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho}$.
- If $\Gamma; \Phi \vdash \mathbb{0}$ then $\llbracket \Gamma; \Phi \vdash \mathbb{0} \rrbracket^{\text{Set}} f = id_0$.
- If $\Gamma; \Phi \vdash \mathbb{1}$ then $\llbracket \Gamma; \Phi \vdash \mathbb{1} \rrbracket^{\text{Set}} f = id_1$.
- If $\Gamma; \Phi \vdash \phi \bar{\tau}$, then we have that $\llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Set}} f : \llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Set}} \rho \rightarrow \llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Set}} \rho' = (\rho\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \rightarrow (\rho'\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'$ is defined by $\llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Set}} f = (f\phi)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} \circ (\rho\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f = (\rho'\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f \circ (f\phi)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}$. This equality holds because $\rho\phi$ and $\rho'\phi$ are functors and $f\phi : \rho\phi \rightarrow \rho'\phi$ is a natural transformation, so that the following naturality square commutes:

$$\begin{array}{ccc} (\rho\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho & \xrightarrow{(f\phi)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}} & (\rho'\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \\ (\rho\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f \downarrow & & (\rho'\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f \downarrow \\ (\rho\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho' & \xrightarrow{(f\phi)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'}} & (\rho'\phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho' \end{array} \quad (1)$$

- If $\Gamma; \Phi \vdash \sigma + \tau$ then $\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Set}} f$ is defined by $\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Set}} f(\text{inl } x) = \text{inl}(\llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} f x)$ and $\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Set}} f(\text{inr } y) = \text{inr}(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f y)$.
- If $\Gamma; \Phi \vdash \sigma \times \tau$ then $\llbracket \Gamma; \Phi \vdash \sigma \times \tau \rrbracket^{\text{Set}} f = \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} f \times \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f$.
- If $\Gamma; \Phi \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\tau}$ we define

$$\begin{aligned} & \llbracket \Gamma; \Phi \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\tau} \rrbracket^{\text{Set}} f \\ & : \llbracket \Gamma; \Phi \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\tau} \rrbracket^{\text{Set}} \rho \rightarrow \llbracket \Gamma; \Phi \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\tau} \rrbracket^{\text{Set}} \rho' \\ & = (\mu T_{\rho}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \rightarrow (\mu T_{\rho'}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho' \end{aligned}$$

by

$$\begin{aligned} & (\mu\sigma_f^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho' \circ (\mu T_{\rho'}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f \\ & = (\mu T_{\rho'}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f \circ (\mu\sigma_f^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \end{aligned}$$

Again, this equality holds because $\mu T_{\rho}^{\text{Set}}$ and $\mu T_{\rho'}^{\text{Set}}$ are functors and $\mu\sigma_f^{\text{Set}} : \mu T_{\rho}^{\text{Set}} \rightarrow \mu T_{\rho'}^{\text{Set}}$ is a natural transformation, so that the following naturality square commutes:

$$\begin{array}{ccc} (\mu T_{\rho}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho & \xrightarrow{(\mu\sigma_f^{\text{Set}})_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}} & (\mu T_{\rho'}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \\ (\mu T_{\rho}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f \downarrow & & (\mu T_{\rho'}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f \downarrow \\ (\mu T_{\rho}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho' & \xrightarrow{(\mu\sigma_f^{\text{Set}})_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'}} & (\mu T_{\rho'}^{\text{Set}}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho' \end{array} \quad (2)$$

3.2 Interpreting Types as Relations

DEFINITION 12. A k -ary relation transformer F is a triple (F^1, F^2, F^*) , where $F^1, F^2 : [\text{Set}^k, \text{Set}]$ are functors, $F^* : [\text{Rel}^k, \text{Rel}]$ is a functor, if $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, then $F^*\bar{R} : \text{Rel}(F^1\bar{A}, F^2\bar{B})$, and if $(\alpha_1, \beta_1) \in \text{Hom}_{\text{Rel}}(R_1, S_1), \dots, (\alpha_k, \beta_k) \in \text{Hom}_{\text{Rel}}(R_k, S_k)$ then $F^*(\alpha, \beta) = (F^1\bar{\alpha}, F^2\bar{\beta})$. We define $F\bar{R}$ to be $F^*\bar{R}$ and $F(\alpha, \beta)$ to be $F^*(\alpha, \beta)$.

Expanding the last clause of Definition 12 is equivalent to: if $\overline{(a, b)} \in R$ implies $\overline{(\alpha a, \beta b)} \in S$ then $(c, d) \in F^*\bar{R}$ implies $(F^1\bar{\alpha} c, F^2\bar{\beta} d) \in F^*\bar{S}$.

When convenient we identify a 0-ary relation transformer (A, B, R) with $R : \text{Rel}(A, B)$. We may also write F^1 and F^2 for $\pi_1 F$ and $\pi_2 F$. We extend these conventions to relation environments, introduced in Definition 19 below, as well.

DEFINITION 13. The category RT_k of k -ary relation transformers is given by the following data:

- An object of RT_k is a relation transformer.
- A morphism $\delta : (G^1, G^2, G^*) \rightarrow (H^1, H^2, H^*)$ in RT_k is a pair of natural transformations (δ^1, δ^2) where $\delta^1 : G^1 \rightarrow H^1$, $\delta^2 : G^2 \rightarrow H^2$ such that, for all $\bar{R} : \text{Rel}(A, B)$, if $(x, y) \in G^*\bar{R}$ then $(\delta^1 x, \delta^2 y) \in H^*\bar{R}$. *Comment that this is basically a fibred natural transformation, but for heterogeneous relations.*
- Identity morphisms and composition are inherited from the category of functors on Set.

DEFINITION 14. An endofunctor H on RT_k is a triple $H = (H^1, H^2, H^*)$, where

- H^1 and H^2 are functors from $[\text{Set}^k, \text{Set}]$ to $[\text{Set}^k, \text{Set}]$
- H^* is a functor from RT_k to $[\text{Rel}^k, \text{Rel}]$
- for all $\bar{R} : \text{Rel}(A, B)$, $\pi_1((H^*(\delta^1, \delta^2))_{\bar{R}}) = (H^1\delta^1)_{\bar{A}}$ and $\pi_2((H^*(\delta^1, \delta^2))_{\bar{R}}) = (H^2\delta^2)_{\bar{B}}$
- The action of H on objects is given by $H(F^1, F^2, F^*) = (H^1F^1, H^2F^2, H^*(F^1, F^2, F^*))$
- The action of H on morphisms is given by $H(\delta^1, \delta^2) = (H^1\delta^1, H^2\delta^2)$ for $(\delta^1, \delta^2) : (F^1, F^2, F^*) \rightarrow (G^1, G^2, G^*)$

Since the results of applying H to k -ary relation transformers and morphisms between them must again be k -ary relation transformers and morphisms between them, respectively, Definition 14 implicitly requires that the following three conditions hold:

- (1) if $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, then

$$H^*(F^1, F^2, F^*)\bar{R} : \text{Rel}(H^1F^1\bar{A}, H^2F^2\bar{B})$$

In other words, $\pi_1(H^*(F^1, F^2, F^*)\bar{R}) = H^1F^1\bar{A}$ and $\pi_2(H^*(F^1, F^2, F^*)\bar{R}) = H^2F^2\bar{B}$.

- (2) if $(\alpha_1, \beta_1) \in \text{Hom}_{\text{Rel}}(R_1, S_1), \dots, (\alpha_k, \beta_k) \in \text{Hom}_{\text{Rel}}(R_k, S_k)$, then

$$H^*(F^1, F^2, F^*)(\alpha, \beta) = (H^1F^1\bar{\alpha}, H^2F^2\bar{\beta})$$

In other words, $\pi_1(H^*(F^1, F^2, F^*)(\alpha, \beta)) = H^1F^1\bar{\alpha}$ and $\pi_2(H^*(F^1, F^2, F^*)(\alpha, \beta)) = H^2F^2\bar{\beta}$.

- (3) if $(\delta^1, \delta^2) : (F^1, F^2, F^*) \rightarrow (G^1, G^2, G^*)$ and $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, then

$$\text{if } (x, y) \in H^*(F^1, F^2, F^*)\bar{R} \text{ then } ((H^1\delta^1)_{\bar{A}}x, (H^2\delta^2)_{\bar{B}}y) \in H^*(G^1, G^2, G^*)\bar{R}$$

Note, however, that this condition is automatically satisfied because it is implied by the third bullet point of Definition 14.

DEFINITION 15. If H and K are endofunctors on RT_k , then a natural transformation $\sigma : H \rightarrow K$ is a pair $\sigma = (\sigma^1, \sigma^2)$, where $\sigma^1 : H^1 \rightarrow K^1$ and $\sigma^2 : H^2 \rightarrow K^2$ are natural transformations between endofunctors on $[\text{Set}^k, \text{Set}]$ and the component of σ at the k -ary relation transformer F is given by $\sigma_F = (\sigma_{F^1}^1, \sigma_{F^2}^2)$.

Definition 15 entails that σ_{Fi}^i must be natural in $F^i : [\text{Set}^k, \text{Set}]$, and, for every F , both $(\sigma_{F1}^1)_{\bar{A}}$ and $(\sigma_{F2}^2)_{\bar{A}}$ must be natural in \bar{A} . Moreover, since the results of applying σ to k -ary relation transformers must be morphisms of k -ary relation transformers, Definition 15 implicitly requires that $(\sigma_F)_{\bar{R}} = ((\sigma_{F1}^1)_{\bar{A}}, (\sigma_{F2}^2)_{\bar{B}})$ is a morphism in Rel for any k -tuple of relations $\bar{R} : \text{Rel}(A, B)$, i.e., if $(x, y) \in H^* \bar{F} \bar{R}$, then $((\sigma_{F1}^1)_{\bar{A}} x, (\sigma_{F2}^2)_{\bar{B}} y) \in K^* \bar{F} \bar{R}$.

Next, we see that we can compute colimits in RT_k .

LEMMA 16. $\lim_{d \in \mathcal{D}} (F_d^1, F_d^2, F_d^*) = (\lim_{d \in \mathcal{D}} F_d^1, \lim_{d \in \mathcal{D}} F_d^2, \lim_{d \in \mathcal{D}} F_d^*)$

PROOF. We first observe that $(\lim_{d \in \mathcal{D}} F_d^1, \lim_{d \in \mathcal{D}} F_d^2, \lim_{d \in \mathcal{D}} F_d^*)$ is in RT_k . If $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, then $\lim_{d \in \mathcal{D}} F_d^* \bar{R} : \text{Rel}(\lim_{d \in \mathcal{D}} F_d^1 \bar{A}, \lim_{d \in \mathcal{D}} F_d^2 \bar{B})$ because of how colimits are computed in Rel . Moreover, if $(\alpha_1, \beta_1) \in \text{Hom}_{\text{Rel}}(R_1, S_1), \dots, (\alpha_k, \beta_k) \in \text{Hom}_{\text{Rel}}(R_k, S_k)$, then

$$\begin{aligned} & (\lim_{d \in \mathcal{D}} F_d^*) (\overline{(\alpha, \beta)}) \\ &= \lim_{d \in \mathcal{D}} F_d^* (\alpha, \beta) \\ &= \lim_{d \in \mathcal{D}} (F_d^1 \bar{\alpha}, F_d^2 \bar{\beta}) \\ &= (\lim_{d \in \mathcal{D}} F_d^1 \bar{\alpha}, \lim_{d \in \mathcal{D}} F_d^2 \bar{\beta}) \end{aligned}$$

so $(\lim_{d \in \mathcal{D}} F_d^1, \lim_{d \in \mathcal{D}} F_d^2, \lim_{d \in \mathcal{D}} F_d^*)$ actually is in RT_k .

Now to see that $\lim_{d \in \mathcal{D}} (F_d^1, F_d^2, F_d^*) = (\lim_{d \in \mathcal{D}} F_d^1, \lim_{d \in \mathcal{D}} F_d^2, \lim_{d \in \mathcal{D}} F_d^*)$, let $\gamma_d^1 : F_d^1 \rightarrow \lim_{d \in \mathcal{D}} F_d^1$ and $\gamma_d^2 : F_d^2 \rightarrow \lim_{d \in \mathcal{D}} F_d^2$ be the injections for the colimits $\lim_{d \in \mathcal{D}} F_d^1$ and $\lim_{d \in \mathcal{D}} F_d^2$, respectively. Then $(\gamma_d^1, \gamma_d^2) : (F_d^1, F_d^2, F_d^*) \rightarrow \lim_{d \in \mathcal{D}} (F_d^1, F_d^2, F_d^*)$ is a morphism in RT_k because, for all $\bar{R} : \text{Rel}(A, B)$, $((\gamma_d^1)_{\bar{A}}, (\gamma_d^2)_{\bar{B}}) : F_d^* \bar{R} \rightarrow \lim_{d \in \mathcal{D}} F_d^* \bar{R}$ is a morphism in Rel . So $\{(\gamma_d^1, \gamma_d^2)\}_{d \in \mathcal{D}}$ are the mediating morphisms of a cocone in RT_k with vertex $\lim_{d \in \mathcal{D}} (F_d^1, F_d^2, F_d^*)$. To see that this cocone is a colimiting cocone, let $C = (C^1, C^2, C^*)$ be the vertex of a cocone for $\{(F_d^1, F_d^2, F_d^*)\}_{d \in \mathcal{D}}$ with injections $(\delta_d^1, \delta_d^2) : (F_d^1, F_d^2, F_d^*) \rightarrow C$. If $\eta^1 : \lim_{d \in \mathcal{D}} F_d^1 \rightarrow C^1$ and $\eta^2 : \lim_{d \in \mathcal{D}} F_d^2 \rightarrow C^2$ are the mediating morphisms in $[\text{Set}^k, \text{Set}]$, then η^1 and η^2 are unique such that $\delta_d^1 = \eta^1 \circ \gamma_d^1$ and $\delta_d^2 = \eta^2 \circ \gamma_d^2$. We therefore have that $(\eta^1, \eta^2) : \lim_{d \in \mathcal{D}} (F_d^1, F_d^2, F_d^*) \rightarrow C$ is the mediating morphism in RT_k . Indeed, for all $\bar{R} : \text{Rel}(A, B)$ and $(x, y) \in \lim_{d \in \mathcal{D}} F_d^* \bar{R}$, there exist d and $(x', y') \in F_d^* \bar{R}$ such that $(\gamma_d^1)_{\bar{A}} x' = x$ and $(\gamma_d^2)_{\bar{B}} y' = y$. But then $(\eta_{\bar{A}}^1 x, \eta_{\bar{B}}^2 y) = (\eta_{\bar{A}}^1 ((\gamma_d^1)_{\bar{A}} x'), \eta_{\bar{B}}^2 ((\gamma_d^2)_{\bar{B}} y')) = ((\delta_d^1)_{\bar{A}} x', (\delta_d^2)_{\bar{B}} y')$, and this pair is in $C^* \bar{R}$ because (δ_d^1, δ_d^2) is a morphism from (F_d^1, F_d^2, F_d^*) to C in RT_k . \square

DEFINITION 17. An endofunctor $T = (T^1, T^2, T^*)$ on RT_k is ω -cocontinuous if T^1 and T^2 are ω -cocontinuous endofunctors on $[\text{Set}^k, \text{Set}]$ and T^* is an ω -cocontinuous functor from RT_k to $[\text{Rel}^k, \text{Rel}]$, i.e., is in $[RT_k, [\text{Rel}^k, \text{Rel}]]$.

For any k and $R : \text{Rel}(A, B)$, let K_R^{Rel} be the constantly R -valued functor from Rel^k to Rel , and for any k and set A , let K_A^{Set} be the constantly A -valued functor from Set^k to Set . Moreover, let 0 denote either the initial object of Set or the initial object of Rel , depending on the context. Observing that, for every k , K_0^{Set} is initial in $[\text{Set}^k, \text{Set}]$, and similarly for K_0^{Rel} , we have that, for each k , $K_0 = (K_0^{\text{Set}}, K_0^{\text{Set}}, K_0^{\text{Rel}})$ is initial in RT_k . Thus, if $T = (T^1, T^2, T^*) : RT_k \rightarrow RT_k$ is an endofunctor on RT_k then we can define μT to be the relation transformer

$$\mu T = \lim_{n \in \mathbb{N}} T^n K_0$$

Then Lemma 16 shows μT is indeed a relation transformer, and that it is given explicitly by

$$\lim_{\rightarrow n \in \mathbb{N}} T^n K_0 = (\mu T^1, \mu T^2, \lim_{\rightarrow n \in \mathbb{N}} (T^n K_0)^*) \quad (3)$$

LEMMA 18. For any $T : [RT_k, RT_k]$, $\mu T \cong T(\mu T)$.

PROOF. We have $T(\mu T) = T(\lim_{\rightarrow n \in \mathbb{N}} (T^n K_0)) \cong \lim_{\rightarrow n \in \mathbb{N}} T(T^n K_0) = \mu T$. \square

In fact, the isomorphism in Lemma 18 is given by the morphisms $(in_1, in_2) : T(\mu T) \rightarrow \mu T$ and $(in_1^{-1}, in_2^{-1}) : \mu T \rightarrow T(\mu T)$ in RT_k . It is worth noting that the latter is always a morphism in RT_k , but the former isn't necessarily a morphism in RT_k unless T is ω -cocontinuous.

Say realizing that not being able to define third components directly, but rather only through the other two components, is an important conceptual contribution. Not all functors on Rel are third components of relation transformers. It's overly restrictive to require that the third component of a functor on RT_k be a functor on all of $[\text{Rel}^k, \text{Rel}]$. For example, we can define $T_\rho F$ when F is a relation transformer, but it is not clear how we could define $T_\rho F$ when $F : [\text{Rel}^k, \text{Rel}]$.

DEFINITION 19. A relation environment maps each type variable in $\mathbb{T}^k \cup \mathbb{F}^k$ to an ω -cocontinuous k -ary relation transformer. A morphism $f : \rho \rightarrow \rho'$ from a relation environment ρ to a relation environment ρ' with $\rho|_{\mathbb{T}} = \rho'|_{\mathbb{T}}$ maps each type constructor variable $\psi^k \in \mathbb{T}$ to the identity morphism on $\rho\psi^k = \rho'\psi^k$ and maps each functorial variable $\phi^k \in \mathbb{F}$ to a morphism from the k -ary relation transformer $\rho\phi$ to the k -ary relation transformer $\rho'\phi$. Composition of morphisms on relation environments is given componentwise, with the identity morphism mapping each relation environment to itself. This gives a category of relation environments and morphisms between them, which we denote RelEnv .

When convenient we identify a 0-ary relation transformer with the relation (transformer) that is its codomain. With this convention, a relation environment maps a type variable of arity 0 to a 0-ary relation transformer — i.e., to a relation. We write $\rho[\alpha := \bar{R}]$ for the relation environment ρ' such that $\rho'\alpha_i = R_i$ for $i = 1, \dots, k$ and $\rho'\alpha = \rho\alpha$ if $\alpha \notin \{\alpha_1, \dots, \alpha_k\}$. If ρ is a relation environment, we write $\pi_1\rho$ for the set environment mapping each type variable ϕ to the functor $(\rho\phi)^1$. The set environment $\pi_2\rho$ similarly maps each type variable ϕ to the functor $(\rho\phi)^2$.

We define, for each k , the notion of an ω -cocontinuous functor from RelEnv to RT_k :

DEFINITION 20. A functor $H : [\text{RelEnv}, RT_k]$ is a triple $H = (H^1, H^2, H^*)$, where

- H^1 and H^2 are objects in $[\text{SetEnv}, [\text{Set}^k, \text{Set}]]$
- H^* is a an object in $[\text{RelEnv}, [\text{Rel}^k, \text{Rel}]]$
- for all $\bar{R} : \text{Rel}(A, B)$ and morphisms f in RelEnv , $\pi_1(H^* f \bar{R}) = H^1(\pi_1 f) \bar{A}$ and $\pi_2(H^* f \bar{R}) = H^2(\pi_2 f) \bar{B}$
- The action of H on ρ in RelEnv is given by $H\rho = (H^1(\pi_1\rho), H^2(\pi_2\rho), H^*\rho)$
- The action of H on morphisms $f : \rho \rightarrow \rho'$ in RelEnv is given by $Hf = (H^1(\pi_1 f), H^2(\pi_2 f))$

Spelling out the last two bullet points above gives the following analogues of Conditions (1), (2), and (3) immediately following Definition 14:

- (1) if $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, then

$$H^* \rho \bar{R} : \text{Rel}(H^1(\pi_1\rho) \bar{A}, H^2(\pi_2\rho) \bar{B})$$

In other words, $\pi_1(H^* \rho \bar{R}) = H^1(\pi_1\rho) \bar{A}$ and $\pi_2(H^* \rho \bar{R}) = H^2(\pi_2\rho) \bar{B}$.

- (2) if $(\alpha_1, \beta_1) \in \text{Hom}_{\text{Rel}}(R_1, S_1), \dots, (\alpha_k, \beta_k) \in \text{Hom}_{\text{Rel}}(R_k, S_k)$, then

$$H^* \rho (\bar{\alpha}, \bar{\beta}) = (H^1(\pi_1\rho) \bar{\alpha}, H^2(\pi_2\rho) \bar{\beta})$$

In other words, $\pi_1(H^* \rho (\bar{\alpha}, \bar{\beta})) = H^1(\pi_1\rho) \bar{\alpha}$ and $\pi_2(H^* \rho (\bar{\alpha}, \bar{\beta})) = H^2(\pi_2\rho) \bar{\beta}$.

(3) if $f : \rho \rightarrow \rho'$ and $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, then

$$\text{if } (x, y) \in H^* \rho \bar{R} \text{ then } (H^1(\pi_1 f) \bar{A} x, H^2(\pi_2 f) \bar{B} y) \in H^* \rho' \bar{R}$$

Note, however, that this condition is automatically satisfied because it is implied by the third bullet point of Definition 20.

Considering RelEnv as a product $\prod_{\phi^k \in \mathbb{T} \cup \mathbb{F}} RT_k$, we extend Lemma 16 to compute colimits in RelEnv componentwise, and similarly extend Definition 17 to give a componentwise notion of ω -cocontinuity of functors from RelEnv to RT_k .

We recall from the start of this section that Definition 21 is given mutually inductively with Definition 10. We can, at last, define:

DEFINITION 21. *Let ρ be a relation environment. The relation interpretation $\llbracket \cdot \rrbracket^{\text{Rel}} : \mathcal{F} \rightarrow [\text{RelEnv}, \text{Rel}]$ is defined by*

$$\begin{aligned} \llbracket \Gamma; \emptyset \vdash v \rrbracket^{\text{Rel}} \rho &= \rho v \text{ if } v \in \mathbb{T}^0 \\ \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho &= \{ \eta : \lambda \bar{R}. \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := \bar{R}] \Rightarrow \lambda \bar{R}. \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := \bar{R}] \} \\ &= \{ (t, t') \in \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}(\pi_1 \rho) \times \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}(\pi_2 \rho) \mid \\ &\quad \forall R_1 : \text{Rel}(A_1, B_1) \dots R_k : \text{Rel}(A_k, B_k). \\ &\quad (t_{\bar{A}}, t'_{\bar{B}}) \in (\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := \bar{R}])^{\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := \bar{R}]} \} \\ &= \{ (t, t') \in \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}(\pi_1 \rho) \times \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}(\pi_2 \rho) \mid \\ &\quad \forall R_1 : \text{Rel}(A_1, B_1) \dots R_k : \text{Rel}(A_k, B_k). \\ &\quad \forall (a, b) \in \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := \bar{R}]. \\ &\quad (t_{\bar{A}} a, t'_{\bar{B}} b) \in \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := \bar{R}] \} \\ \llbracket \Gamma; \Phi \vdash 0 \rrbracket^{\text{Rel}} \rho &= 0 \\ \llbracket \Gamma; \Phi \vdash 1 \rrbracket^{\text{Rel}} \rho &= 1 \\ \llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Rel}} \rho &= (\rho \phi) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho} \\ \llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Rel}} \rho &= \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} \rho + \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho \\ \llbracket \Gamma; \Phi \vdash \sigma \times \tau \rrbracket^{\text{Rel}} \rho &= \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} \rho \times \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho \\ \llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Rel}} \rho &= (\mu T_\rho) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho} \\ &\text{where } T_\rho = (T_{\pi_1 \rho}^{\text{Set}}, T_{\pi_2 \rho}^{\text{Set}}, T_\rho^{\text{Rel}}) \\ &\text{and } T_\rho^{\text{Rel}} F = \lambda \bar{R}. \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} \rho[\phi := F][\bar{\alpha} := \bar{R}] \\ &\text{and } T_\rho^{\text{Rel}} \delta = \lambda \bar{R}. \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} id_\rho[\phi := \delta][\bar{\alpha} := id_{\bar{R}}] \end{aligned}$$

The interpretations in Definition 21 respect weakening, i.e., a type and its weakenings all have the same relational interpretations. The same holds for the actions of these interpretations on morphisms in Definition 22 below. Moreover, the interpretation of Nat types ensures that $\llbracket \Gamma \vdash \sigma \rightarrow \tau \rrbracket^{\text{Rel}} \rho = \llbracket \Gamma \vdash \sigma \rrbracket^{\text{Rel}} \rho \rightarrow \llbracket \Gamma \vdash \tau \rrbracket^{\text{Rel}} \rho$, as expected. If ρ is a relational environment and $\vdash \tau : \mathcal{F}$, then we write $\llbracket \vdash \tau \rrbracket^{\text{Rel}}$ instead of $\llbracket \vdash \tau \rrbracket^{\text{Rel}} \rho$ as for set interpretations.

For the last clause in Definition 21 to be well-defined, we need to know that T_ρ is an ω -cocontinuous endofunctor on RT so that, by Lemma 18, it admits a fixed point. Since T_ρ is defined in terms of $\llbracket \Gamma; \Phi, \phi^k, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}}$, this means that relational interpretations of types must be

ω -cocontinuous functors from RelEnv to RT_0 . This in turn means that the actions of relational interpretations of types on objects and on morphisms in RelEnv are intertwined. In fact, we already know from [Johann and Polonsky 2019] that, for every $\Gamma; \bar{\alpha} \vdash \tau : \mathcal{F}$, $\llbracket \Gamma; \bar{\alpha} \vdash \tau \rrbracket^{\text{Rel}}$ is actually functorial in $\bar{\alpha}$ and ω -cocontinuous. We first define the actions of each of these functors on morphisms between environments, and then argue that the functors given by Definitions 21 and 22 are well-defined and have the required properties. As in the case of the set interpretations, each operator T Should be T_H , really, and similarly throughout. can be extended to a *functor* from RelEnv to $[[\text{Rel}^k, \text{Rel}], [\text{Rel}^k, \text{Rel}]]$. Its action on an object $\rho \in \text{RelEnv}$ is given by the higher-order functor $T_\rho^{\text{Rel}} T_{H,\rho}^{\text{Rel}}$ whose actions on objects and morphisms are as defined in Definition 22. The action of T on a morphism $f : \rho \rightarrow \rho'$ is the higher-order natural transformation May want to use $T_{H,f}$ rather than σ_f in the final version. $\sigma_f : T_\rho \rightarrow T_{\rho'}$ whose action on any $F : [\text{Rel}^k, \text{Rel}]$ is the natural transformation $\sigma_f F : T_\rho F \rightarrow T_{\rho'} F$ whose component at \bar{R} is

$$(\sigma_f F)_{\bar{R}} = \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} f[\phi := id_F][\bar{\alpha} := id_{\bar{R}}]$$

The next definition uses this observation to define the action of each functor interpreting a type on morphisms between relation environments.

DEFINITION 22. Let $f : \rho \rightarrow \rho'$ for relation environments ρ and ρ' (so that $\rho|_{\mathbb{T}} = \rho'|_{\mathbb{T}}$). The action $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f$ of $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}}$ on the morphism f is given as follows:

- If $\Gamma, v; \emptyset \vdash v$ then $\llbracket \Gamma, v; \emptyset \vdash v \rrbracket^{\text{Rel}} f = id_{\rho v}$.
- If $\Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G$, then we define $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} f = id_{\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho}$.
- If $\Gamma; \Phi \vdash \emptyset$ then $\llbracket \Gamma; \Phi \vdash \emptyset \rrbracket^{\text{Rel}} f = id_0$.
- If $\Gamma; \Phi \vdash \mathbb{1}$ then $\llbracket \Gamma; \Phi \vdash \mathbb{1} \rrbracket^{\text{Rel}} f = id_1$.
- If $\Gamma; \Phi \vdash \phi \bar{\tau}$, then we have that $\llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Rel}} f : \llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Rel}} \rho \rightarrow \llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Rel}} \rho' = (\rho \phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho \rightarrow (\rho' \phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho'$ is defined by $\llbracket \Gamma; \Phi \vdash \phi \tau A \rrbracket^{\text{Rel}} f = (f \phi)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho'} \circ (\rho \phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f = (\rho' \phi) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f \circ (f \phi)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho}$.
- If $\Gamma; \Phi \vdash \sigma + \tau$ then $\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Rel}} f$ is defined by $\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Rel}} f(\text{inl } x) = \text{inl } (\llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} f x)$ and $\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Rel}} f(\text{inr } y) = \text{inr } (\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f y)$.
- If $\Gamma; \Phi \vdash \sigma \times \tau$ then $\llbracket \Gamma; \Phi \vdash \sigma \times \tau \rrbracket^{\text{Rel}} f = \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} f \times \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f$.
- If $\Gamma; \Phi \vdash (\mu \phi^k. \lambda \bar{\alpha}. H) \bar{\tau}$ we define

$$\begin{aligned} & \llbracket \Gamma; \Phi \vdash (\mu \phi^k. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Rel}} f \\ &= (\mu \sigma_f) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho' \circ (\mu T_\rho) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f \\ &= (\mu T_{\rho'}) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f \circ (\mu \sigma_f) \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho \end{aligned}$$

To see that the functors given by Definitions 21 and 22 are well-defined we must show that $T_\rho F$ is a relation transformer for any relation transformer F , and that $\sigma_f F : T_\rho F \rightarrow T_{\rho'} F$ is a morphism of relation transformers for every relation transformer F and every morphism $f : \rho \rightarrow \rho'$ in RelEnv .

LEMMA 23. The interpretations in Definitions 21 and 22 are well-defined and, for every $\Gamma; \Phi \vdash \tau$,

$$\llbracket \Gamma; \Phi \vdash \tau \rrbracket = (\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}, \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}, \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}})$$

is an ω -cocontinuous functor from RelEnv to RT_0 , i.e., is an element of $[\text{RelEnv}, RT_0]$.

PROOF. By induction on the structure of τ . The only interesting cases are when $\tau = \phi \bar{\tau}$ and when $\tau = (\mu \phi^k. \lambda \bar{\alpha}. H) \bar{\tau}$. We consider each in turn.

- When $\tau = \Gamma; \Phi \vdash \phi\bar{\tau}$, we have

$$\begin{aligned}
 & \pi_i(\llbracket \Gamma; \Phi \vdash \phi\bar{\tau} \rrbracket^{\text{Rel}} \rho) \\
 &= \pi_i((\rho\phi)(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho)) \\
 &= (\pi_i(\rho\phi))(\pi_i(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho)) \\
 &= ((\pi_i\rho)\phi)(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_i\rho)) \\
 &= \llbracket \Gamma; \Phi \vdash \phi\bar{\tau} \rrbracket^{\text{Set}}(\pi_i\rho)
 \end{aligned}$$

and, for $f : \rho \rightarrow \rho'$ in RelEnv ,

$$\begin{aligned}
 & \pi_i(\llbracket \Gamma; \Phi \vdash \phi\bar{\tau} \rrbracket^{\text{Rel}} f) \\
 &= \pi_i((f\phi)(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho')) \circ \pi_i((\rho\phi)(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f)) \\
 &= (\pi_i(f\phi))(\pi_i(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho')) \circ (\pi_i(\rho\phi))(\pi_i(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f)) \\
 &= ((\pi_i f)\phi)(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_i\rho')) \circ ((\pi_i\rho)\phi)(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_i f)) \\
 &= \llbracket \Gamma; \Phi \vdash \phi\bar{\tau} \rrbracket^{\text{Set}}(\pi_i f)
 \end{aligned}$$

The third equalities of each of the above derivations are by the induction hypothesis. That $\llbracket \Gamma; \Phi \vdash \phi\bar{\tau} \rrbracket$ is ω -cocontinuous is an immediate consequence of the facts that Set and Rel are locally finitely presentable, together with Corollary 12 of [Johann and Polonsky 2019].

- When $\tau = (\mu\phi.\lambda\bar{\alpha}.H)\bar{\tau}$ we first show that $\llbracket (\mu\phi.\lambda\bar{\alpha}.H)\bar{\tau} \rrbracket$ is well-defined.
 – $T_\rho : [RT_k, RT_k]$: We must show that, for any relation transformer $F = (F^1, F^2, F^*)$, the triple $T_\rho F = (T_{\pi_1\rho}^{\text{Set}} F^1, T_{\pi_2\rho}^{\text{Set}} F^2, T_\rho^{\text{Rel}} F)$ is also a relation transformer. Let $\bar{R} : \text{Rel}(A, B)$. Then for $i = 1, 2$, we have

$$\begin{aligned}
 \pi_i(T_\rho^{\text{Rel}} F \bar{R}) &= \pi_i(\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} \rho[\phi := F][\bar{\alpha} := \bar{R}]) \\
 &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}}(\pi_i(\rho[\phi := F][\bar{\alpha} := \bar{R}])) \\
 &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}}(\pi_i\rho[\phi := \pi_i F][\bar{\alpha} := \pi_i \bar{R}]) \\
 &= T_{\pi_i\rho}^{\text{Set}}(\pi_i F)(\pi_i \bar{R})
 \end{aligned}$$

and

$$\begin{aligned}
 \pi_i(T_\rho^{\text{Rel}} F \bar{\gamma}) &= \pi_i(\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} id_\rho[\phi := id_F][\bar{\alpha} := \bar{\gamma}]) \\
 &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}}(\pi_i(id_\rho[\phi := id_F][\bar{\alpha} := \bar{\gamma}])) \\
 &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} id_{\pi_i\rho}[\phi := id_{\pi_i F}][\bar{\alpha} := \pi_i \bar{\gamma}] \\
 &= T_{\pi_i\rho}^{\text{Set}}(\pi_i F)(\pi_i \bar{\gamma})
 \end{aligned}$$

Here, the second equality in each of the above chains of equalities is by the induction hypothesis.

We also have that, for every morphism $\delta = (\delta^1, \delta^2) : F \rightarrow G$ in RT_k and all $\bar{R} : \text{Rel}(A, B)$,

$$\begin{aligned}
 & \pi_i((T_\rho^{\text{Rel}} \delta)_{\bar{R}}) \\
 &= \pi_i(\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} id_\rho[\phi := \delta][\bar{\alpha} := id_{\bar{R}}]) \\
 &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} id_{\pi_i\rho}[\phi := \pi_i \delta][\bar{\alpha} := id_{\pi_i \bar{R}}] \\
 &= (T_{\pi_i\rho}^{\text{Set}}(\pi_i \delta))_{\pi_i \bar{R}}
 \end{aligned}$$

Here, the second equality is by the induction hypothesis. That T_ρ is ω -cocontinuous follows immediately from the induction hypothesis on $\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket$ and the fact that colimits are computed componentwise in RT .

– $\sigma_f = (\sigma_{\pi_1 f}^{\text{Set}}, \sigma_{\pi_2 f}^{\text{Set}})$ is a natural transformation from T_ρ to $T_{\rho'}$: We must show that $(\sigma_f)_F = ((\sigma_{\pi_1 f}^{\text{Set}})_{F^1}, (\sigma_{\pi_2 f}^{\text{Set}})_{F^2})$ is a morphism in RT_k for all relation transformers $F = (F^1, F^2, F^*)$, i.e., that $((\sigma_f)_F)_{\bar{R}} = (((\sigma_{\pi_1 f}^{\text{Set}})_{F^1})_{\bar{A}}, ((\sigma_{\pi_2 f}^{\text{Set}})_{F^2})_{\bar{B}})$ is a morphism in Rel for all relations $\bar{R} : \text{Rel}(A, B)$. Indeed, we have that

$$((\sigma_f)_F)_{\bar{R}} = \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} f[\phi := id_F][\bar{\alpha} := id_R]$$

is a morphism in RT_0 (and thus in Rel) by the induction hypothesis.

The relation transformer μT_ρ is therefore a fixed point of T_ρ by Lemma 18, and $\mu \sigma_f$ is a morphism in RT_k from μT_ρ to $\mu T_{\rho'}$. (μ is shown to be a functor in [Johann and Polonsky 2019].) So $\llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Rel}}$, and thus $\llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket$, is well-defined.

To see that $\llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket : [\text{RelEnv}, RT_0]$, we must verify three conditions:

– Condition (1) after Definition 20 is satisfied since

$$\begin{aligned} \pi_i(\llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Rel}} \rho) &= \pi_i((\mu T_\rho)(\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho})) \\ &= \pi_i(\mu T_\rho)(\pi_i(\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho})) \\ &= \mu T_{\pi_i \rho}^{\text{Set}}(\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_i \rho)}) \\ &= \llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Set}}(\pi_i \rho) \end{aligned}$$

The third equality is by Equation 3 and the induction hypothesis.

– Condition (2) after Definition 20 is satisfied since it is subsumed by the previous condition because $k = 0$.

– The third bullet point of Definition 20 is satisfied because

$$\begin{aligned} \pi_i(\llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Rel}} f) &= \pi_i((\mu T_{\rho'})(\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f}) \circ (\mu \sigma_f)_{\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho}}) \\ &= \pi_i((\mu T_{\rho'})(\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f})) \circ \pi_i((\mu \sigma_f)_{\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho}}) \\ &= \pi_i(\mu T_{\rho'}) \circ \pi_i(\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} f}) \circ \pi_i(\mu \sigma_f)_{\overline{\pi_i(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho)}} \\ &= (\mu T_{\pi_i \rho'}^{\text{Set}})(\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_i f)}) \circ (\mu \sigma_{\pi_i f}^{\text{Set}})_{\overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_i \rho)}} \\ &= \llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Set}}(\pi_i f). \end{aligned}$$

The fourth equality is by 3 and the induction hypothesis.

As before, that $\llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket$ is ω -concontinuous follows from the facts that Set and Rel are locally finitely presentable, and that colimits in RelEnv are computed componentwise, together with Corollary 12 of [Johann and Polonsky 2019].

□

The following lemma ensures that substitution interacts well with type interpretations. It is a consequence of Definitions 6, 33, and 34.

LEMMA 24. *Let ρ be a set environment ρ and $f : \rho \rightarrow \rho'$ be a morphism of set environments.*

- *If $\Gamma; \Phi, \bar{\alpha} \vdash F$ and $\Gamma; \Phi \vdash \tau$, then*

$$\llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho = \llbracket \Gamma; \Phi, \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \quad (4)$$

and

$$\llbracket \Gamma; \Phi \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}} f = \llbracket \Gamma; \Phi, \bar{\alpha} \vdash F \rrbracket^{\text{Set}} f[\overline{\alpha := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f}] \quad (5)$$

- If $\Gamma; \Phi, \phi^k \vdash F$ and $\Gamma; \Phi, \alpha_1 \dots \alpha_k \vdash H$, then

$$\llbracket \Gamma; \Phi \vdash F[\phi := H] \rrbracket^{\text{Set}} \rho = \llbracket \Gamma; \Phi, \phi \vdash F \rrbracket^{\text{Set}} \rho[\phi := \lambda \bar{A}. \llbracket \Gamma; \Phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\overline{\alpha := A}]] \quad (6)$$

and

$$\llbracket \Gamma; \Phi \vdash F[\phi := H] \rrbracket^{\text{Set}} f = \llbracket \Gamma; \Phi, \phi \vdash F \rrbracket^{\text{Set}} f[\phi := \lambda \bar{A}. \llbracket \Gamma; \Phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} f[\overline{\alpha := id_{\bar{A}}}]] \quad (7)$$

Analogous identities hold for relation environments and morphisms between them.

PROOF. The proofs for the set and relational interpretations are completely analogous, so we just prove the former. Likewise, we only prove Equations 4 and 6, since the proofs for Equations 5 and 7 are again analogous. Finally, we prove Equation 4 for substitution for just a single type variable since the proof for multiple simultaneous substitutions proceeds similarly.

Although Equation 4 is a special case of Equation 6, it is convenient to prove Equation 4 first, and then use it to prove Equation 6. We prove Equation 4 by induction on the structure of F as follows:

- If $\Gamma; \emptyset \vdash F : \mathcal{T}$, or if F is $\mathbb{1}$ or $\mathbb{0}$, then F does not contain any functorial variables to replace, so there is nothing to prove.
- If F is $F_1 \times F_2$ or $F_1 + F_2$, then the substitution distributes over the product or coproduct as appropriate, so the result follows immediately from the induction hypothesis.
- If $F = \beta$ with $\beta \neq \alpha$, then there is nothing to prove.
- If $F = \alpha$, then

$$\llbracket \Gamma; \Phi \vdash \alpha[\alpha := \tau] \rrbracket^{\text{Set}} \rho = \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho = \llbracket \Gamma; \Phi, \alpha \vdash \alpha \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho]$$

- If $F = \phi \bar{\sigma}$ with $\phi \neq \alpha$, then

$$\begin{aligned} & \llbracket \Gamma; \Phi \vdash (\phi \bar{\sigma})[\alpha := \tau] \rrbracket^{\text{Set}} \rho \\ &= \llbracket \Gamma; \Phi \vdash \phi(\overline{\sigma[\alpha := \tau]}) \rrbracket^{\text{Set}} \rho \\ &= (\rho\phi) \llbracket \Gamma; \Phi \vdash \sigma[\alpha := \tau] \rrbracket^{\text{Set}} \rho \\ &= (\rho\phi) \llbracket \Gamma; \Phi, \alpha \vdash \sigma \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \\ &= \llbracket \Gamma; \Phi, \alpha \vdash \phi \bar{\sigma} \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \end{aligned}$$

Here, the third equality is by the induction hypothesis.

- If $F = (\mu\phi. \lambda\bar{\beta}. G)\bar{\sigma}$, then

$$\begin{aligned} & \llbracket \Gamma; \Phi \vdash ((\mu\phi. \lambda\bar{\beta}. G)\bar{\sigma})[\alpha := \tau] \rrbracket^{\text{Set}} \rho \\ &= \llbracket \Gamma; \Phi \vdash (\mu\phi. \lambda\bar{\beta}. G[\alpha := \tau])(\overline{\sigma[\alpha := \tau]}) \rrbracket^{\text{Set}} \rho \\ &= \mu(\llbracket \Gamma; \Phi, \phi, \bar{\beta} \vdash G[\alpha := \tau] \rrbracket^{\text{Set}} \rho[\phi := -][\bar{\beta} := -])(\llbracket \Gamma; \Phi \vdash \sigma[\alpha := \tau] \rrbracket^{\text{Set}} \rho) \\ &= \mu(\llbracket \Gamma; \Phi, \phi, \bar{\beta}, \alpha \vdash G \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho][\phi := -][\bar{\beta} := -]) \\ & \quad (\llbracket \Gamma; \Phi, \alpha \vdash \sigma \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho]) \\ &= \llbracket \Gamma; \Phi, \alpha \vdash (\mu\phi. \lambda\bar{\beta}. G)\bar{\sigma} \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \end{aligned}$$

Here, the third equality is by the induction hypothesis and weakening.

We now prove Equation 6, again by induction on the structure of F .

- If $\Gamma; \emptyset \vdash F : \mathcal{T}$, or if F is $\mathbb{1}$ or $\mathbb{0}$, then F does not contain any functorial variables to replace, so there is nothing to prove.
- If F is $F_1 \times F_2$ or $F_1 + F_2$, then the substitution distributes over the product or coproduct as appropriate, so the result follows immediately from the induction hypothesis.

- If $F = \phi\bar{\tau}$, then

$$\begin{aligned}
& \llbracket \Gamma; \Phi \vdash (\phi\bar{\tau})[\phi := H] \rrbracket^{\text{Set}} \rho \\
&= \llbracket \Gamma; \Phi \vdash H[\alpha := \tau[\phi := H]] \rrbracket^{\text{Set}} \rho \\
&= \llbracket \Gamma; \Phi \vdash H \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \tau[\phi := H] \rrbracket^{\text{Set}} \rho] \\
&= \llbracket \Gamma; \Phi \vdash H \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho[\phi := \llbracket \Gamma; \Phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\bar{\alpha} := -]]] \\
&= \llbracket \Gamma; \Phi, \phi \vdash \phi\bar{\tau} \rrbracket^{\text{Set}} \rho[\phi := \llbracket \Gamma; \Phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\bar{\alpha} := -]]
\end{aligned}$$

Here, the first equality is by Definition 6, the second is by Equation 4, the third is by the induction hypothesis, and the fourth is by Definition 10.

- If $F = \psi\bar{\tau}$ with $\psi \neq \phi$, then the proof is similar to that for the previous case, but simpler, because ϕ only needs to be substituted in the arguments $\bar{\tau}$ of ψ .
- If $F = (\mu\psi.\lambda\bar{\beta}.G)\bar{\tau}$, then

$$\begin{aligned}
& \llbracket \Gamma; \Phi \vdash ((\mu\psi.\lambda\bar{\beta}.G)\bar{\tau})[\phi := H] \rrbracket^{\text{Set}} \rho \\
&= \llbracket \Gamma; \Phi \vdash (\mu\psi.\lambda\bar{\beta}.G[\phi := H])(\bar{\tau}[\phi := H]) \rrbracket^{\text{Set}} \rho \\
&= \mu(\llbracket \Gamma; \Phi, \psi, \bar{\beta} \vdash G[\phi := H] \rrbracket^{\text{Set}} \rho[\psi := -][\bar{\beta} := -])(\llbracket \Gamma; \Phi \vdash \bar{\tau}[\phi := H] \rrbracket^{\text{Set}} \rho) \\
&= \mu(\llbracket \Gamma; \Phi, \psi, \bar{\beta}, \phi \vdash G \rrbracket^{\text{Set}} \rho[\phi := \llbracket \Gamma; \Phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\bar{\alpha} := -]][\psi := -][\bar{\beta} := -]) \\
&\quad (\llbracket \Gamma; \Phi, \phi \vdash \tau \rrbracket^{\text{Set}} \rho[\phi := \llbracket \Gamma; \Phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\bar{\alpha} := -]]) \\
&= \llbracket \Gamma; \Phi, \phi \vdash (\mu\psi.\lambda\bar{\beta}.G)\bar{\tau} \rrbracket^{\text{Set}} \rho[\phi := \llbracket \Gamma; \Phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\bar{\alpha} := -]]
\end{aligned}$$

Here, the first equality is by Definition 6, the second and fourth are by Definition 10, and the third is by the induction hypothesis and weakening.

□

3.3 The Identity Extension Lemma

The standard definition of graph relation of a morphism in Set is

DEFINITION 25. If $f : A \rightarrow B$ then the relation $\langle f \rangle : \text{Rel}(A, B)$ is defined by $(x, y) \in \langle f \rangle$ iff $fx = y$.

Here, we are using angle bracket notation for both the graph relation of a function and for the pairing of functions with the same domain. This is justified by the relationship between the two notions observed immediately after Lemma ??.

We extend the notion of a graph to natural transformations between k -ary set functors by defining an associated k -ary relation transformer.

DEFINITION 26. If $F, G : \text{Set}^k \rightarrow \text{Set}$ are k -ary set functors and $\alpha : F \rightarrow G$ is a natural transformation, we define the functor $\langle \alpha \rangle^* : \text{Rel}^k \rightarrow \text{Rel}$ as follows. Given $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, let $\iota_{R_i} : R_i \hookrightarrow A_i \times B_i$, for $i = 1, \dots, k$, be the inclusion of R_i as a subset of $A_i \times B_i$. By the universal property of the product, there exists a unique $h_{A \times B}$ making the diagram

$$\begin{array}{ccccc}
F\bar{A} & \xleftarrow{F\bar{\pi}_1} & F(\bar{A} \times \bar{B}) & \xrightarrow{F\bar{\pi}_2} & F\bar{B} & \xrightarrow{\alpha_{\bar{B}}} & G\bar{B} \\
& \swarrow \pi_1 & \downarrow h_{A \times B} & & \searrow \pi_2 & & \\
& & F\bar{A} \times G\bar{B} & & & &
\end{array}$$

commute. Let $h_{\bar{R}} : F\bar{R} \rightarrow F\bar{A} \times G\bar{B}$ be $h_{\bar{A} \times \bar{B}} \circ F\iota_{\bar{R}}$. Define $\alpha^{\wedge} \bar{R}$ to be the subobject through which $h_{\bar{R}}$ is factorized by the mono-epi factorization system in \mathbf{Set} , as shown in the following diagram:

$$\begin{array}{ccc} F\bar{R} & \xrightarrow{h_{\bar{R}}} & F\bar{A} \times G\bar{B} \\ & \searrow q_{\alpha^{\wedge} \bar{R}} & \nearrow \iota_{\alpha^{\wedge} \bar{R}} \\ & \alpha^{\wedge} \bar{R} & \end{array}$$

Since $\alpha^{\wedge} \bar{R} : \mathbf{Rel}(F\bar{A}, G\bar{B})$ by construction, we define $\langle \alpha \rangle^*(\bar{A}, \bar{B}, \bar{R}) = (F\bar{A}, G\bar{B}, \iota_{\alpha^{\wedge} \bar{R}} \alpha^{\wedge} \bar{R})$. Moreover, if $(\beta, \beta') : (A, B, R) \rightarrow (C, D, S)$ are morphisms in \mathbf{Rel} , then we define $\langle \alpha \rangle^*(\beta, \beta')$ to be $(F\bar{\beta}, G\bar{\beta}')$.

The data in Definition 26 yield a relation transformer.

LEMMA 27. If $\alpha : F \rightarrow G$ is a morphism in $[\mathbf{Set}^k, \mathbf{Set}]$, i.e., a natural transformation between ω -cocontinuous functors, then $\langle \alpha \rangle = (F, G, \langle \alpha \rangle^*)$ is in RT_k .

PROOF. Clearly, $\langle \alpha \rangle^*$ is ω -cocontinuous, so $\langle \alpha \rangle^* : [\mathbf{Rel}^k, \mathbf{Rel}]$.

Now, consider $(\beta, \beta') : R \rightarrow S$, where $R : \mathbf{Rel}(A, B)$ and $S : \mathbf{Rel}(C, D)$. We want to show that there exists a morphism $\epsilon : \alpha^{\wedge} \bar{R} \rightarrow \alpha^{\wedge} \bar{S}$ such that

$$\begin{array}{ccc} \alpha^{\wedge} \bar{R} & \xrightarrow{\iota_{\alpha^{\wedge} \bar{R}}} & F\bar{A} \times G\bar{B} \\ \epsilon \downarrow & & \downarrow F\bar{\beta} \times G\bar{\beta}' \\ \alpha^{\wedge} \bar{S} & \xrightarrow{\iota_{\alpha^{\wedge} \bar{S}}} & F\bar{C} \times G\bar{D} \end{array}$$

commutes. Since $(\beta, \beta') : R \rightarrow S$, there exist $\gamma : R \rightarrow S$ such that each diagram

$$\begin{array}{ccc} R_i & \xrightarrow{\iota_{R_i}} & A_i \times B_i \\ \gamma_i \downarrow & & \downarrow \beta_i \times \beta'_i \\ S_i & \xrightarrow{\iota_{S_i}} & C_i \times D_i \end{array}$$

commutes. Now note that both $h_{\bar{C} \times \bar{D}} \circ F(\bar{\beta} \times \bar{\beta}')$ and $(F\bar{\beta} \times G\bar{\beta}') \circ h_{\bar{A} \times \bar{B}}$ make

$$\begin{array}{ccccc} F\bar{C} & \xleftarrow{\pi_1} & F\bar{C} \times F\bar{D} & \xrightarrow{\pi_2} & F\bar{D} & \xrightarrow{\alpha_{\bar{D}}} & G\bar{D} \\ & \nwarrow F\pi_1 \circ F(\bar{\beta} \times \bar{\beta}') & \uparrow \exists! & \nearrow \alpha_{\bar{D}} \circ F\pi_2 \circ F(\bar{\beta} \times \bar{\beta}') & & & \\ & & F(\bar{A} \times \bar{B}) & & & & \end{array}$$

commute, so they must be equal. We therefore get that the right-hand square below commutes, and thus that the entire following diagram does as well:

$$\begin{array}{ccccc} & & h_{\bar{R}} & & \\ & \searrow & \downarrow & \searrow & \\ F\bar{R} & \xrightarrow{F\iota_{\bar{R}}} & F(\bar{A} \times \bar{B}) & \xrightarrow{h_{\bar{A} \times \bar{B}}} & F\bar{A} \times G\bar{B} \\ F\bar{\gamma} \downarrow & & \downarrow F(\bar{\beta} \times \bar{\beta}') & & \downarrow F\bar{\beta} \times G\bar{\beta}' \\ F\bar{S} & \xrightarrow{F\iota_{\bar{S}}} & F(\bar{C} \times \bar{D}) & \xrightarrow{h_{\bar{C} \times \bar{D}}} & F\bar{C} \times G\bar{D} \\ & \searrow & \downarrow & \searrow & \\ & & h_{\bar{S}} & & \end{array}$$

Finally, by the left-lifting property of $q_{F \wedge \bar{R}}$ with respect to $\iota_{F \wedge \bar{S}}$ given by the epi-mono factorization system, there exists an ϵ such that the diagram

$$\begin{array}{ccccc} F\bar{R} & \xrightarrow{q_{\alpha \wedge \bar{R}}} & \alpha \wedge \bar{R} & \xrightarrow{\iota_{\alpha \wedge \bar{R}}} & F\bar{A} \times G\bar{B} \\ F\bar{Y} \downarrow & & \downarrow \epsilon & & \downarrow F\bar{\beta} \times G\bar{\beta}' \\ F\bar{S} & \xrightarrow{q_{\alpha \wedge \bar{S}}} & \alpha \wedge \bar{S} & \xrightarrow{\iota_{\alpha \wedge \bar{S}}} & F\bar{C} \times G\bar{D} \end{array}$$

commutes. □

If $f : A \rightarrow B$ be a function with graph relation $\langle f \rangle = (A, B, \langle f \rangle^*)$, then $\langle id_A, f \rangle : A \rightarrow A \times B$ and $\langle id_A, f \rangle A = \langle f \rangle^*$. Moreover, if $\iota_{\langle f \rangle} : \langle f \rangle^* \hookrightarrow A \times B$ is the inclusion of $\langle f \rangle^*$ into $A \times B$ then there is an isomorphism of subobjects

$$\begin{array}{ccc} A & \xrightarrow{\cong} & \langle f \rangle^* \\ & \searrow \langle id_A, f \rangle & \swarrow \iota_{\langle f \rangle} \\ & A \times B & \end{array}$$

We also note that if $f : A \rightarrow B$ is a function seen as a natural transformation between 0-ary functors, then $\langle f \rangle$ is (the 0-ary relation transformer associated with) the graph relation of f . Indeed, we need to apply Definition 26 with $k = 0$, i.e., to the degenerate relation $*$: $\text{Rel}(*, *)$. As degenerate 0-ary functors, A and B are constant functors, i.e., $A* = A$ and $B* = B$. By the universal property of the product, there exists a unique h making the diagram

$$\begin{array}{ccccc} A & \xlongequal{\quad} & A & \xlongequal{\quad} & A \xrightarrow{f} B \\ & \searrow \pi_1 & \downarrow h & \swarrow \pi_2 & \\ & A \times B & & & \end{array}$$

commute. Since $\iota_* : * \rightarrow *$ is the identity on $*$, and $A id_* = id_A$, we have $h_* = h$. Moreover, $h_{A \times B} = \langle id_A, f \rangle$ is a monomorphism in Set because id_A is. Then, $\iota_{f^*} = \langle id_A, f \rangle$ and $f^* = A$, from which we deduce that $\iota_{f^*} f^* = \langle id_A, f \rangle A = \langle f \rangle^*$. This ensures that the graph of f as a 0-ary natural transformation coincides with the graph of f as a morphism in Set , and so that Definition 26 is a reasonable generalization of Definition 25.

Just as the equality relation Eq_B on a set B coincides with $\langle id_B \rangle$, the graph of the identity on the set, so we can define the equality relation transformer to be the graph of the identity natural transformation. This gives

DEFINITION 28. Let $F : [\text{Set}^k, \text{Set}]$. The equality relation transformer on F is defined to be $\text{Eq}_F = \langle id_F \rangle$. This entails that $\text{Eq}_F = (F, F, \text{Eq}_F^*)$ with $\text{Eq}_F^* = \langle id_F \rangle^*$.

The graph relation transformer on a graph relation is easily computed:

LEMMA 29. If $\alpha : F \rightarrow G$ is a morphism in $[\text{Set}^k, \text{Set}]$ and $f_1 : A_1 \rightarrow B_1, \dots, f_k : A_k \rightarrow B_k$, then $\langle \alpha \rangle^* \langle f \rangle = \langle Gf \circ \alpha_A \rangle = \langle \alpha_B \circ Ff \rangle$.

PROOF. Since $h_{\overline{A \times B}}$ is the unique morphism making the bottom triangle of the following diagram commute

$$\begin{array}{ccccc}
 & & \overline{F\overline{A}} & & \\
 & \swarrow & \downarrow F\langle id_{\overline{A}}, f \rangle & \searrow F\overline{f} & \\
 \overline{F\overline{A}} & \xleftarrow{F\overline{\pi_1}} & \overline{F(A \times B)} & \xrightarrow{F\overline{\pi_2}} & \overline{F\overline{B}} & \xrightarrow{\alpha_{\overline{B}}} & \overline{G\overline{B}} \\
 & \nwarrow \pi_1 & \downarrow h_{\overline{A \times B}} & \nearrow \pi_2 & & \\
 & & \overline{F\overline{A}} \times \overline{G\overline{B}} & &
 \end{array}$$

and since $h_{\langle \overline{f} \rangle} = h_{\overline{A \times B}} \circ F\overline{\iota_{\langle f \rangle}} = h_{\overline{A \times B}} \circ F\langle id_{\overline{A}}, f \rangle$, the universal property of the product

$$\begin{array}{ccccc}
 \overline{F\overline{A}} & \xleftarrow{\pi_1} & \overline{F\overline{A}} \times \overline{G\overline{B}} & \xrightarrow{\pi_2} & \overline{G\overline{B}} \\
 & \searrow & \uparrow \exists! & & \uparrow \alpha_{\overline{B}} \\
 & & \overline{F\overline{A}} & \xrightarrow{F\overline{f}} & \overline{F\overline{B}}
 \end{array}$$

gives that $h_{\langle \overline{f} \rangle} = \langle id_{\overline{F\overline{A}}}, \alpha_{\overline{B}} \circ F\overline{f} \rangle : \overline{F\overline{A}} \rightarrow \overline{F\overline{A}} \times \overline{G\overline{B}}$. Moreover, $\langle id_{\overline{F\overline{A}}}, \alpha_{\overline{B}} \circ F\overline{f} \rangle$ is a monomorphism in Set because $id_{\overline{F\overline{A}}}$ is, so its epi-mono factorization gives that $\iota_{\alpha^{\wedge} \langle \overline{f} \rangle} = \langle id_{\overline{F\overline{A}}}, \alpha_{\overline{B}} \circ F\overline{f} \rangle$, and thus that $\alpha^{\wedge} \langle \overline{f} \rangle$, the domain of $\iota_{\alpha^{\wedge} \langle \overline{f} \rangle}$ is equal to $\overline{F\overline{A}}$. Then, $\iota_{\alpha^{\wedge} \langle \overline{f} \rangle} \alpha^{\wedge} \langle \overline{f} \rangle = \langle id_{\overline{F\overline{A}}}, \alpha_{\overline{B}} \circ F\overline{f} \rangle (F\overline{A}) = \langle \alpha_{\overline{B}} \circ F\overline{f} \rangle^*$. We therefore conclude that $\langle \alpha \rangle^* \langle \overline{f} \rangle = (F\overline{A}, G\overline{B}, \iota_{\alpha^{\wedge} \langle \overline{f} \rangle} \alpha^{\wedge} \langle \overline{f} \rangle) = (F\overline{A}, G\overline{B}, \langle \alpha_{\overline{B}} \circ F\overline{f} \rangle^*) = \langle \alpha_{\overline{B}} \circ F\overline{f} \rangle$.

Finally, note that $\alpha_{\overline{B}} \circ F\overline{f} = G\overline{f} \circ \alpha_{\overline{A}}$ by naturality of α . \square

As an immediate corollary we have

COROLLARY 30. If $F : [\text{Set}^k, \text{Set}]$ and $\overline{A} : \text{Set}$, then $\text{Eq}_F^* \overline{\text{Eq}_A} = \text{Eq}_{F\overline{A}}$.

PROOF. We have that

$$\text{Eq}_F^* \overline{\text{Eq}_A} = \langle id_F \rangle^* \langle id_{\overline{A}} \rangle = \langle F id_{\overline{A}} \circ (id_F)_{\overline{A}} \rangle = \langle id_{F\overline{A}} \circ id_{F\overline{A}} \rangle = \langle id_{F\overline{A}} \rangle = \text{Eq}_{F\overline{A}}$$

The second identity here is by Lemma 29. \square

We can extend the notions of the graph of a natural transformation and the equality relation transformer to environments as follows:

Definition 3.1. Let $f : \rho \rightarrow \rho'$ is a morphism of set environments. The graph relation environment $\langle f \rangle$ is defined pointwise, i.e., for any variable ϕ , we define $\langle f \rangle \phi = \langle f \phi \rangle$. This ensures that $\pi_1 \langle f \rangle = \rho$ and $\pi_2 \langle f \rangle = \rho'$. Then the equality relation environment Eq_ρ for any set environment ρ is then defined to be $\langle id_\rho \rangle$.

With this definition in hand, we can prove an Identity Extension Lemma for our type interpretations.

THEOREM 31. If ρ is a set environment, and $\Gamma; \Phi \vdash \tau : \mathcal{F}$, then $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \text{Eq}_\rho = \text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}$.

PROOF. By induction on the structure of τ .

- $\llbracket \Gamma; \emptyset \vdash v \rrbracket^{\text{Rel}} \text{Eq}_\rho = \text{Eq}_{\rho v} = \text{Eq}_{\rho v} = \text{Eq}_{\llbracket \Gamma; \emptyset \vdash v \rrbracket^{\text{Set}} \rho}$ where $v \in \Gamma$.

- By definition, $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \text{Eq}_{\rho}$ is the relation on $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}_{\rho}$ relating t and t' if, for all $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, $(t_{\bar{A}}, t'_{\bar{B}})$ is a morphism from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ in Rel. To prove that this is equal to $\text{Eq}_{\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}_{\rho}}$ we need to show that $(t_{\bar{A}}, t'_{\bar{B}})$ is a morphism from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ in Rel for all $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$ if and only if $t = t'$ and $(t_{\bar{A}}, t'_{\bar{B}})$ is a morphism from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ in Rel for all $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$. The only interesting part of this equivalence is to show that if $(t_{\bar{A}}, t'_{\bar{B}})$ is a morphism from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := R]$ in Rel for all $R_1 : \text{Rel}(A_1, B_1), \dots, R_k : \text{Rel}(A_k, B_k)$, then $t = t'$. By hypothesis, $(t_{\bar{A}}, t'_{\bar{A}})$ is a morphism from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := \text{Eq}_A]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_{\rho} [\alpha := \text{Eq}_A]$ in Rel for all $A_1 \dots A_k : \text{Set}$. By the induction hypothesis, it is therefore a morphism from $\text{Eq}_{\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}}_{\rho} [\alpha := A]}$ to $\text{Eq}_{\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}}_{\rho} [\alpha := A]}$ in Rel. This means that, for every $x : \text{Eq}_{\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}}_{\rho} [\alpha := A]}$, $t_{\bar{A}} x = t'_{\bar{A}} x$. Then, by extensionality, $t = t'$.
- $\llbracket \Gamma; \Phi \vdash 0 \rrbracket^{\text{Rel}} \text{Eq}_{\rho} = 0_{\text{Rel}} = \text{Eq}_{0_{\text{Set}}} = \text{Eq}_{\llbracket \Gamma; \Phi \vdash 0 \rrbracket^{\text{Set}}_{\rho}}$
- $\llbracket \Gamma; \Phi \vdash 1 \rrbracket^{\text{Rel}} \text{Eq}_{\rho} = 1_{\text{Rel}} = \text{Eq}_{1_{\text{Set}}} = \text{Eq}_{\llbracket \Gamma; \Phi \vdash 1 \rrbracket^{\text{Set}}_{\rho}}$
- The application case is proved by the following sequence of equalities, where the second equality is by the induction hypothesis and the definition of the relation environment Eq_{ρ} , the third is by the definition of application of relation transformers from Definition 12, and the fourth is by Lemma 29:

$$\begin{aligned}
 \llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Rel}} \text{Eq}_{\rho} &= (\text{Eq}_{\rho} \phi) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \text{Eq}_{\rho}} \\
 &= \text{Eq}_{\rho} \phi \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \\
 &= (\text{Eq}_{\rho} \phi)^* \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \\
 &= \text{Eq}_{(\rho \phi) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \\
 &= \text{Eq}_{\llbracket \Gamma; \Phi \vdash \phi \bar{\tau} \rrbracket^{\text{Set}}_{\rho}}
 \end{aligned}$$

- The fixed point case is proven by the sequence of equalities

$$\begin{aligned}
 \llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Rel}} \text{Eq}_{\rho} &= (\mu T_{\text{Eq}_{\rho}}) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \text{Eq}_{\rho}} \\
 &= \lim_{n \in \mathbb{N}} T_{\text{Eq}_{\rho}}^n K_0 \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \text{Eq}_{\rho}} \\
 &= \lim_{n \in \mathbb{N}} T_{\text{Eq}_{\rho}}^n K_0 \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \\
 &= \lim_{n \in \mathbb{N}} (\text{Eq}_{(T_{\rho}^{\text{Set}})^n K_0})^* \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \\
 &= \lim_{n \in \mathbb{N}} \text{Eq}_{(T_{\rho}^{\text{Set}})^n K_0 \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \\
 &= \text{Eq}_{\lim_{n \in \mathbb{N}} (T_{\rho}^{\text{Set}})^n K_0 \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \\
 &= \text{Eq}_{\llbracket \Gamma; \Phi \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\tau} \rrbracket^{\text{Set}}_{\rho}}
 \end{aligned}$$

Here, the third equality is by induction hypothesis, the fifth is by Lemma 29 and the fourth equality is because, for every $n \in \mathbb{N}$, the following two statements can be proved by simultaneous induction:

$$T_{\text{Eq}_{\rho}}^n K_0 \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} = (\text{Eq}_{(T_{\rho}^{\text{Set}})^n K_0})^* \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}_{\rho}}} \quad (8)$$

and

$$\begin{aligned} & \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := T_{\text{Eq}_\rho}^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \\ &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := \text{Eq}_{(T_\rho^{\text{Set}})^n K_0}][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \end{aligned} \quad (9)$$

We prove (8). The case $n = 0$ is trivial, because $T_{\text{Eq}_\rho}^0 K_0 = K_0$ and $(T_\rho^{\text{Set}})^0 K_0 = K_0$; the inductive step is proved by the following sequence of equalities:

$$\begin{aligned} T_{\text{Eq}_\rho}^{n+1} K_0 \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}} &= T_{\text{Eq}_\rho}^{\text{Rel}}(T_{\text{Eq}_\rho}^n K_0) \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}} \\ &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := T_{\text{Eq}_\rho}^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \\ &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := \text{Eq}_{(T_\rho^{\text{Set}})^n K_0}][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \\ &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := (T_\rho^{\text{Set}})^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \\ &= \text{Eq}_{\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho}[\phi := (T_\rho^{\text{Set}})^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \\ &= \text{Eq}_{(T_\rho^{\text{Set}})^{n+1} K_0} \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}} \\ &= (\text{Eq}_{(T_\rho^{\text{Set}})^{n+1} K_0})^* \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}} \end{aligned}$$

Here, the third equality is by (9), the fifth by the induction hypothesis on H , and the last by Lemma 29. We prove the induction step of (9) by structural induction on H : the only interesting case, though, is when ϕ is applied, i.e., for $H = \phi\bar{\sigma}$, which is proved by the sequence of equalities:

$$\begin{aligned} & \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \phi\bar{\sigma} \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := T_{\text{Eq}_\rho}^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \\ &= T_{\text{Eq}_\rho}^n K_0 \overline{\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \sigma \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := T_{\text{Eq}_\rho}^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}]} \\ &= T_{\text{Eq}_\rho}^n K_0 \overline{\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \sigma \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := \text{Eq}_{(T_\rho^{\text{Set}})^n K_0}][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}]} \\ &= T_{\text{Eq}_\rho}^n K_0 \overline{\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \sigma \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := (T_\rho^{\text{Set}})^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}]} \\ &= T_{\text{Eq}_\rho}^n K_0 \overline{\text{Eq}_{\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \sigma \rrbracket^{\text{Set}} \rho}[\phi := (T_\rho^{\text{Set}})^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}]} \\ &= (\text{Eq}_{(T_\rho^{\text{Set}})^n K_0})^* \overline{\text{Eq}_{\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \sigma \rrbracket^{\text{Set}} \rho}[\phi := (T_\rho^{\text{Set}})^n K_0][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}]} \\ &= (\text{Eq}_{(T_\rho^{\text{Set}})^n K_0})^* \overline{\llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \sigma \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := \text{Eq}_{(T_\rho^{\text{Set}})^n K_0}][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}]} \\ &= \llbracket \Gamma; \Phi, \phi, \bar{\alpha} \vdash \phi\bar{\sigma} \rrbracket^{\text{Rel}} \text{Eq}_\rho[\phi := \text{Eq}_{(T_\rho^{\text{Set}})^n K_0}][\bar{\alpha} := \overline{\text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}}] \end{aligned}$$

Here, the second equality is by the induction hypothesis for (9) on the σ s, the fourth is by the induction hypothesis for Theorem 31 on the σ s, and the fifth is by the induction hypothesis on n for (8).

- $\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Rel}} \text{Eq}_\rho = \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} \text{Eq}_\rho + \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \text{Eq}_\rho = \text{Eq}_{\llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho} + \text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} = \text{Eq}_{\llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho + \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} = \text{Eq}_{\llbracket \Gamma; \Phi \vdash \sigma + \tau \rrbracket^{\text{Set}} \rho}$
- $\llbracket \Gamma; \Phi \vdash \sigma \times \tau \rrbracket^{\text{Rel}} \text{Eq}_\rho = \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} \text{Eq}_\rho \times \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \text{Eq}_\rho = \text{Eq}_{\llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho} \times \text{Eq}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} = \text{Eq}_{\llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho \times \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} = \text{Eq}_{\llbracket \Gamma; \Phi \vdash \sigma \times \tau \rrbracket^{\text{Set}} \rho}$

□

It follows from Theorem 31 that $\llbracket \Gamma \vdash \sigma \rightarrow \tau \rrbracket^{\text{Rel}} \text{Eq}_\rho = \text{Eq}_{\llbracket \Gamma \vdash \sigma \rightarrow \tau \rrbracket^{\text{Set}} \rho}$, as expected. Moreover, the Identity Extension Lemma also allows us to prove a Graph Lemma.

LEMMA 32 (GRAPH LEMMA). *If $f : \rho \rightarrow \rho'$ is a morphism of set environments and $\Gamma; \Phi \vdash F : \mathcal{F}$, then $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f = \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$*

PROOF. First observe that $(f, id_{\rho'}) : \langle f \rangle \rightarrow \text{Eq}_{\rho'}$ and $(id_{\rho}, f) : \text{Eq}_{\rho} \rightarrow \langle f \rangle$ are morphisms of relation environments. Applying Lemma 23 to each of these observations gives that

$$(\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} id_{\rho'}) = \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} (f, id_{\rho'}) : \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle \rightarrow \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho'} \quad (10)$$

and

$$(\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} id_{\rho}, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f) = \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} (id_{\rho}, f) : \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho} \rightarrow \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle \quad (11)$$

Expanding Equation 10 gives that if $(x, y) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$ then

$$(\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} id_{\rho'} y) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho'}$$

Observe that $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} id_{\rho'} y = id_{\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho'} y = y$ and $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \text{Eq}_{\rho'} = \text{Eq}_{\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho'}$. So, if $(x, y) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$ then $(\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x, y) \in \text{Eq}_{\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho'}$, i.e., $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x = y$, i.e., $(x, y) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f$. So, we have that $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle \subseteq \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f$

Expanding Equation 11 gives that, for any $x \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho$, then

$$(\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} id_{\rho} x, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$$

Observe that $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} id_{\rho} x = id_{\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho} x = x$ so, for any $x \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho$, we have that $(x, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$. Moreover, $x \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho$ if and only if $(x, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f$ and, if $x \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} \rho$ then $(x, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$, so if $(x, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f$ then $(x, \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f x) \in \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$, i.e., $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f \subseteq \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle$. We conclude that $\llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Rel}} \langle f \rangle = \llbracket \Gamma; \Phi \vdash F \rrbracket^{\text{Set}} f$ as desired. \square

4 INTERPRETING TERMS

If $\Delta = x_1 : \tau_1, \dots, x_n : \tau_n$ is a term context for Γ and Φ , then the interpretations $\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}}$ and $\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}}$ are defined by

$$\begin{aligned} \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} &= \llbracket \Gamma; \Phi \vdash \tau_1 \rrbracket^{\text{Set}} \times \dots \times \llbracket \Gamma; \Phi \vdash \tau_n \rrbracket^{\text{Set}} \\ \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} &= \llbracket \Gamma; \Phi \vdash \tau_1 \rrbracket^{\text{Rel}} \times \dots \times \llbracket \Gamma; \Phi \vdash \tau_n \rrbracket^{\text{Rel}} \end{aligned}$$

Every well-formed term $\Gamma; \Phi \mid \Delta \vdash t : \tau$ then has, for every $\rho \in \text{SetEnv}$, set interpretations $\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} \rho$ as natural transformations from $\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho$ to $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho$, and, for every $\rho \in \text{RelEnv}$, relational interpretations $\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho$ as natural transformations from $\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rho$ to $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho$. These are given in the next two definitions.

DEFINITION 33. If ρ is a set environment and $\Gamma; \Phi \mid \Delta \vdash t : \tau$ then $\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} \rho$ is defined as follows:

$$\begin{aligned}
& \llbracket \Gamma; \emptyset \mid \Delta, x : \tau \vdash x : \tau \rrbracket^{\text{Set}} \rho &= \pi_{|\Delta|+1} \\
& \llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x. t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho &= \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho [\bar{\alpha} := _]) \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho &= \text{eval} \circ \langle \lambda d. (\llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho d) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} \rangle \\
& & \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho \rangle \\
& \llbracket \Gamma; \Phi \mid \Delta, x : \tau \vdash x : \tau \rrbracket^{\text{Set}} \rho &= \pi_{|\Delta|+1} \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \perp_{\tau} t : \tau \rrbracket^{\text{Set}} \rho &= !_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}^0 \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : 0 \rrbracket^{\text{Set}} \rho, \text{ where} \\
& & !_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}^0 \text{ is the unique morphism from } 0 \\
& & \text{to } \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \top : 1 \rrbracket^{\text{Set}} \rho &= !_1^{\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho}, \text{ where } !_1^{\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho} \\
& & \text{is the unique morphism from } \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho \text{ to } 1 \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash (s, t) : \sigma \times \tau \rrbracket^{\text{Set}} \rho &= \llbracket \Gamma; \Phi \mid \Delta \vdash s : \sigma \rrbracket^{\text{Set}} \rho \times \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \pi_1 t : \sigma \rrbracket^{\text{Set}} \rho &= \pi_1 \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : \sigma \times \tau \rrbracket^{\text{Set}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \pi_2 t : \sigma \rrbracket^{\text{Set}} \rho &= \pi_2 \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : \sigma \times \tau \rrbracket^{\text{Set}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \text{case } t \text{ of } \{x \mapsto l; y \mapsto r\} : \gamma \rrbracket^{\text{Set}} \rho &= \text{eval} \circ \langle \text{curry} [\llbracket \Gamma; \Phi \mid \Delta, x : \sigma \vdash l : \gamma \rrbracket^{\text{Set}} \rho, \\
& & \llbracket \Gamma; \Phi \mid \Delta, y : \tau \vdash r : \gamma \rrbracket^{\text{Set}} \rho], \\
& & \llbracket \Gamma; \Phi \mid \Delta \vdash t : \sigma + \tau \rrbracket^{\text{Set}} \rho \rangle \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \text{inl } s : \sigma + \tau \rrbracket^{\text{Set}} \rho &= \text{inl} \circ \llbracket \Gamma; \Phi \mid \Delta \vdash s : \sigma \rrbracket^{\text{Set}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \text{inr } t : \sigma + \tau \rrbracket^{\text{Set}} \rho &= \text{inr} \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} \rho \\
& \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\bar{F}, \bar{G}}^{\bar{F}, \bar{G}} : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) &= \lambda d \bar{\eta} \bar{B}. \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{\rho[\bar{\gamma} := \bar{B}]} [\phi := \lambda \bar{A}. \eta_{\bar{A} \bar{B}}] \\
& \quad (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} := \bar{\beta} \bar{F}] H[\bar{\phi} := \bar{\beta} \bar{G}]) \rrbracket^{\text{Set}} \rho & \\
& \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\bar{\alpha} := \bar{\beta}] &= \lambda d \bar{B} \bar{C}. (\text{in}_{T^{\text{Set}}_{\rho[\bar{\gamma} := \bar{C}]}})_{\bar{B}} \\
& \quad (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho & \\
& \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} := \bar{\beta} F] [\bar{\alpha} := \bar{\beta}] F) &= \lambda d \bar{\eta} \bar{B} \bar{C}. (\text{fold}_{T^{\text{Set}}_{\rho[\bar{\gamma} := \bar{C}]}} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}}))_{\bar{B}} \\
& \quad (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Set}} \rho &
\end{aligned}$$

Add return type for fold in last clause? Should be $\llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho [\bar{\gamma} := \bar{C}]$.

This interpretation gives that $\llbracket \Gamma; \emptyset \mid \Delta \vdash \lambda x. t : \sigma \rightarrow \tau \rrbracket^{\text{Set}} \rho = \text{curry}(\llbracket \Gamma; \emptyset \mid \Delta, x : \sigma \vdash t : \tau \rrbracket^{\text{Set}} \rho)$ and $\llbracket \Gamma; \emptyset \mid \Delta \vdash st : \tau \rrbracket^{\text{Set}} \rho = \text{eval} \circ \langle \llbracket \Gamma; \emptyset \mid \Delta \vdash s : \sigma \rightarrow \tau \rrbracket^{\text{Set}} \rho, \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \sigma \rrbracket^{\text{Set}} \rho \rangle$, as expected.

DEFINITION 34. If ρ is a relation environment and $\Gamma; \Phi \mid \Delta \vdash t : \tau$ then $\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho$ is defined as follows:

$$\begin{aligned}
& \llbracket \Gamma; \emptyset \mid \Delta, x : \tau \vdash x : \tau \rrbracket^{\text{Rel}} \rho &= \pi_{|\Delta|+1} \\
& \llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x. t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho &= \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Rel}} \rho [\bar{\alpha} := _]) \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}} \rho &= \text{eval} \circ \langle \lambda e. (\llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho e) \overline{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho} \rangle \\
& & \quad \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}} \rho \rangle \\
& \llbracket \Gamma; \Phi \mid \Delta, x : \tau \vdash x : \tau \rrbracket^{\text{Rel}} \rho &= \pi_{|\Delta|+1} \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \perp_{\tau} t : \tau \rrbracket^{\text{Rel}} \rho &= \text{!}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho}^0 \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : 0 \rrbracket^{\text{Rel}} \rho, \text{ where} \\
& & \quad \text{!}_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho}^0 \text{ is the unique morphism from } 0 \\
& & \quad \text{to } \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \top : \mathbb{1} \rrbracket^{\text{Rel}} \rho &= \text{!}_1^{\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rho}, \text{ where } \text{!}_1^{\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rho} \\
& & \quad \text{is the unique morphism from } \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rho \text{ to } \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash (s, t) : \sigma \times \tau \rrbracket^{\text{Rel}} \rho &= \llbracket \Gamma; \Phi \mid \Delta \vdash s : \sigma \rrbracket^{\text{Rel}} \rho \times \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \pi_1 t : \sigma \rrbracket^{\text{Rel}} \rho &= \pi_1 \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : \sigma \times \tau \rrbracket^{\text{Rel}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \pi_2 t : \sigma \rrbracket^{\text{Rel}} \rho &= \pi_2 \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : \sigma \times \tau \rrbracket^{\text{Rel}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \text{case } t \text{ of } \{x \mapsto l; y \mapsto r\} : \gamma \rrbracket^{\text{Rel}} \rho &= \text{eval} \circ \langle \text{curry} [\llbracket \Gamma; \Phi \mid \Delta, x : \sigma \vdash l : \gamma \rrbracket^{\text{Rel}} \rho, \\
& & \quad \llbracket \Gamma; \Phi \mid \Delta, y : \tau \vdash r : \gamma \rrbracket^{\text{Rel}} \rho], \\
& & \quad \llbracket \Gamma; \Phi \mid \Delta \vdash t : \sigma + \tau \rrbracket^{\text{Rel}} \rho \rangle \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \text{inl } s : \sigma + \tau \rrbracket^{\text{Rel}} \rho &= \text{inl} \circ \llbracket \Gamma; \Phi \mid \Delta \vdash s : \sigma \rrbracket^{\text{Rel}} \rho \\
& \llbracket \Gamma; \Phi \mid \Delta \vdash \text{inr } t : \sigma + \tau \rrbracket^{\text{Rel}} \rho &= \text{inr} \circ \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho \\
& \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\bar{F}, \bar{G}}^{\bar{F}, \bar{G}} : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) &= \lambda d \bar{\eta} \bar{R}. \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Rel}} \text{id}_{\rho[\bar{\gamma} := \bar{R}]} [\phi := \lambda \bar{S}. \eta \bar{S} \bar{R}] \\
& \quad (\text{Nat}^{\bar{\gamma}} H[\phi := \bar{\beta} F] H[\phi := \bar{\beta} G]) \rrbracket^{\text{Rel}} \rho & \\
& \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\alpha := \bar{\beta}] &= \lambda d \bar{R} \bar{S}. (\text{in}_{T_{\rho[\bar{\gamma} := \bar{S}]}})_{\bar{R}} \\
& \quad (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Rel}} \rho & \\
& \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := \bar{\beta} F] [\alpha := \bar{\beta}] F) &= \lambda d \bar{\eta} \bar{R} \bar{S}. (\text{fold}_{T_{\rho[\bar{\gamma} := \bar{S}]}} (\lambda \bar{Z}. \eta \bar{Z} \bar{S}))_{\bar{R}} \\
& \quad (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Rel}} \rho &
\end{aligned}$$

Add return type for fold in last clause? Should be $\llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Rel}} \rho [\bar{\gamma} := \bar{C}]$.

If t is closed, i.e., if $\emptyset; \emptyset \mid \emptyset \vdash t : \tau$, then we write $\llbracket \vdash t : \tau \rrbracket^{\text{Set}}$ instead of $\llbracket \emptyset; \emptyset \mid \emptyset \vdash t : \tau \rrbracket^{\text{Set}}$, and similarly for $\llbracket \emptyset; \emptyset \mid \emptyset \vdash t : \tau \rrbracket^{\text{Rel}}$.

4.1 Basic Properties of Term Interpretations

This interpretation gives that $\llbracket \Gamma; \emptyset \mid \Delta \vdash \lambda x. t : \sigma \rightarrow \tau \rrbracket^{\text{Rel}} \rho = \text{curry}(\llbracket \Gamma; \emptyset \mid \Delta, x : \sigma \vdash t : \tau \rrbracket^{\text{Rel}} \rho)$ and $\llbracket \Gamma; \emptyset \mid \Delta \vdash st : \tau \rrbracket^{\text{Rel}} \rho = \text{eval} \circ \langle \llbracket \Gamma; \emptyset \mid \Delta \vdash s : \sigma \rightarrow \tau \rrbracket^{\text{Rel}} \rho, \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \sigma \rrbracket^{\text{Rel}} \rho \rangle$, as expected.

The interpretations in Definitions 33 and 34 respect weakening, i.e., a term and its weakenings all have the same set and relational interpretations. In particular, for any $\rho \in \text{SetEnv}$,

$$\llbracket \Gamma; \Phi \mid \Delta, x : \sigma \vdash t : \tau \rrbracket^{\text{Set}} \rho = (\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} \rho) \circ \pi_{\Delta}$$

where π_{Δ} is the projection $\llbracket \Gamma; \Phi \vdash \Delta, x : \sigma \rrbracket^{\text{Set}} \rightarrow \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}}$, and for any $\rho \in \text{RelEnv}$,

$$\llbracket \Gamma; \Phi \mid \Delta, x : \sigma \vdash t : \tau \rrbracket^{\text{Rel}} \rho = (\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho) \circ \pi_{\Delta}$$

where π_{Δ} is the projection $\llbracket \Gamma; \Phi \vdash \Delta, x : \sigma \rrbracket^{\text{Rel}} \rightarrow \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}}$. Moreover, if $\Gamma, \alpha; \Phi \mid \Delta \vdash t : \tau$ and $\Gamma; \Phi, \alpha \mid \Delta \vdash t' : \tau$ and $\Gamma; \Phi \vdash \sigma : \mathcal{F}$ then

$$\bullet \llbracket \Gamma; \Phi \mid \Delta[\alpha := \sigma] \vdash t[\alpha := \sigma] : \tau[\alpha := \sigma] \rrbracket^{\text{Set}} \rho = \llbracket \Gamma, \alpha; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho]$$

- $\llbracket \Gamma; \Phi \mid \Delta[\alpha := \sigma] \vdash t[\alpha := \sigma] : \tau[\alpha := \sigma] \rrbracket^{\text{Rel}} \rho = \llbracket \Gamma, \alpha; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} \rho]$
- $\llbracket \Gamma; \Phi \mid \Delta[\alpha := \sigma] \vdash t'[\alpha := \sigma] : \tau[\alpha := \sigma] \rrbracket^{\text{Set}} \rho = \llbracket \Gamma; \Phi, \alpha \mid \Delta \vdash t' : \tau \rrbracket^{\text{Set}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Set}} \rho]$
- $\llbracket \Gamma; \Phi \mid \Delta[\alpha := \sigma] \vdash t'[\alpha := \sigma] : \tau[\alpha := \sigma] \rrbracket^{\text{Rel}} \rho = \llbracket \Gamma; \Phi, \alpha \mid \Delta \vdash t' : \tau \rrbracket^{\text{Rel}} \rho[\alpha := \llbracket \Gamma; \Phi \vdash \sigma \rrbracket^{\text{Rel}} \rho]$

and if $\Gamma; \Phi \mid \Delta, x : \sigma \vdash t : \tau$ and $\Gamma; \Phi \mid \Delta \vdash s : \sigma$ then

- $\lambda A. \llbracket \Gamma; \Phi \mid \Delta \vdash t[x := s] : \tau \rrbracket^{\text{Set}} \rho A = \lambda A. \llbracket \Gamma; \Phi \mid \Delta, x : \sigma \vdash t : \tau \rrbracket^{\text{Set}} \rho(A, \llbracket \Gamma; \Phi \mid \Delta \vdash s : \sigma \rrbracket^{\text{Set}} \rho A)$
- $\lambda R. \llbracket \Gamma; \Phi \mid \Delta \vdash t[x := s] : \tau \rrbracket^{\text{Rel}} \rho R = \lambda R. \llbracket \Gamma; \Phi \mid \Delta, x : \sigma \vdash t : \tau \rrbracket^{\text{Rel}} \rho(R, \llbracket \Gamma; \Phi \mid \Delta \vdash s : \sigma \rrbracket^{\text{Rel}} \rho R)$

Direct calculation reveals that the set interpretations of terms also satisfy

- $\llbracket \Gamma; \Phi \mid \Delta \vdash (L_{\bar{\alpha}x}.t)_{\bar{\tau}s} \rrbracket^{\text{Set}} = \llbracket \Gamma; \Phi \mid \Delta \vdash t[\bar{\alpha} := \bar{\tau}][x := s] \rrbracket^{\text{Set}}$

Standard type extensionality $\llbracket \Gamma; \Phi \vdash (L_{\alpha x}.t)_{\alpha t} \rrbracket^{\text{Set}} = \llbracket \Gamma; \Phi \vdash t \rrbracket^{\text{Set}}$ and $\llbracket \Gamma; \Phi \vdash (L_{\alpha x}.t)_{\alpha t} \rrbracket^{\text{Rel}} = \llbracket \Gamma; \Phi \vdash t \rrbracket^{\text{Rel}}$, as well as term extensionality $\llbracket \Gamma; \Phi \vdash (L_{\alpha x}.t)_{\alpha \top} \rrbracket^{\text{Set}} = \llbracket \Gamma; \Phi \vdash t \rrbracket^{\text{Set}}$ and $\llbracket \Gamma; \Phi \vdash (L_{\alpha x}.t)_{\alpha \top} \rrbracket^{\text{Rel}} = \llbracket \Gamma; \Phi \vdash t \rrbracket^{\text{Rel}}$, for terms are immediate consequences.

4.2 Properties of Terms of Nat-Type

If we define, for $\Gamma; \bar{\alpha} \vdash F$, the term id_F to be $\Gamma; \emptyset \mid \emptyset \vdash L_{\bar{\alpha}x}.x : \text{Nat}^{\bar{\alpha}} F F$ and, for terms $\Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G$ and $\Gamma; \emptyset \mid \Delta \vdash s : \text{Nat}^{\bar{\alpha}} G H$, the *composition* $s \circ t$ of t and s to be $\Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}x}.s_{\bar{\alpha}}(t_{\bar{\alpha}x}) : \text{Nat}^{\bar{\alpha}} F H$, then

- $\llbracket \Gamma; \emptyset \mid \emptyset \vdash id_F : \text{Nat}^{\bar{\alpha}} F F \rrbracket^{\text{Set}} \rho = id_{\lambda \bar{A}. \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]}$ for any set environment ρ
- $\llbracket \Gamma; \emptyset \mid \Delta \vdash s \circ t : \text{Nat}^{\bar{\alpha}} F H \rrbracket^{\text{Set}} = \llbracket \Gamma; \emptyset \mid \Delta \vdash s : \text{Nat}^{\bar{\alpha}} G H \rrbracket^{\text{Set}} \circ \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}$

Moreover, terms of Nat type behave as natural transformations with respect to their source and target functorial types.

- $\llbracket \Gamma; \emptyset \mid x : \text{Nat}^{\bar{\alpha}} \bar{y} F G, y : \text{Nat}^{\bar{y}} \sigma \tau \vdash ((\text{map}_{\bar{G}}^{\bar{\sigma}, \bar{\tau}})_{\emptyset \bar{y}}) \circ (L_{\bar{y}z}.x_{\bar{\sigma}, \bar{y}z}) : \text{Nat}^{\bar{y}} F[\bar{\alpha} := \bar{\sigma}] G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}$
 $= \llbracket \Gamma; \emptyset \mid x : \text{Nat}^{\bar{\alpha}} \bar{y} F G, y : \text{Nat}^{\bar{y}} \sigma \tau \vdash (L_{\bar{y}z}.x_{\bar{\tau}, \bar{y}z}) \circ ((\text{map}_{\bar{F}}^{\bar{\sigma}, \bar{\tau}})_{\emptyset \bar{y}}) : \text{Nat}^{\bar{y}} F[\bar{\alpha} := \bar{\sigma}] G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}$

As the special case of the previous equality when $x = in_H$ we have

THEOREM 35. • $\llbracket \Gamma; \emptyset \mid y : \text{Nat}^{\bar{y}} \sigma \tau \vdash ((\text{map}_{(\mu\phi. \lambda \bar{\alpha}. H)_{\bar{\beta}}}^{\bar{\sigma}, \bar{\tau}})_{\emptyset \bar{y}}) \circ (L_{\bar{y}z}.(in_H)_{\bar{\sigma}, \bar{y}z}) : \xi \rrbracket^{\text{Set}}$
 $= \llbracket \Gamma; \emptyset \mid y : \text{Nat}^{\bar{y}} \sigma \tau \vdash (L_{\bar{y}z}.(in_H)_{\bar{\tau}, \bar{y}z}) \circ ((\text{map}_{H[\phi := (\mu\phi. \lambda \bar{\alpha}. H)_{\bar{\beta}}]}^{\bar{\sigma}, \bar{\tau}})_{\emptyset \bar{y}}) : \xi \rrbracket^{\text{Set}}$
 at type $\xi = \text{Nat}^{\bar{y}} H[\phi := (\mu\phi. \lambda \bar{\alpha}. H)_{\bar{\beta}}][\bar{\alpha} := \bar{\sigma}](\mu\phi. \lambda \bar{\alpha}. H)_{\bar{\tau}}$

Analogous results hold for relational interpretations of terms and relational environments.

As we observe in Section 5.1, Theorem 35 gives a family of results that we normally derive as free theorems but actually are consequences of naturality. Most of Wadler's fall into this family, for example, but not the free theorem for filter (even for lists) or short cut fusion.

4.3 Properties of Initial Algebraic Constructs

We first observe that map-terms are interpreted as semantic *maps*:

Let $\Gamma; \bar{\phi}, \bar{y} \vdash H : \mathcal{F}$, $\Gamma; \bar{\beta}, \bar{y} \vdash F : \mathcal{F}$ and $\Gamma; \bar{\beta}, \bar{y} \vdash G : \mathcal{F}$. By definition of the semantic interpretation of map terms, we have

$$\begin{aligned} \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_H^{\bar{F}, \bar{G}} : \text{Nat}^{\emptyset} (\text{Nat}^{\bar{\beta}, \bar{y}} F G) (\text{Nat}^{\bar{y}} H[\bar{\phi} := \bar{\beta} F] H[\bar{\phi} := \bar{\beta} G]) \rrbracket^{\text{Set}} \rho \\ = \lambda d \bar{\eta} \bar{B}. \llbracket \Gamma; \bar{\phi}, \bar{y} \vdash H \rrbracket^{\text{Set}} id_{\rho[\bar{y} := \bar{B}]}[\bar{\phi} := \lambda \bar{A}. \bar{\eta}_{\bar{A} \bar{B}}] \quad (12) \end{aligned}$$

Then let $\Gamma; \bar{\alpha} \vdash F : \mathcal{F}$, $\Gamma; \bar{\theta} \vdash \sigma : \mathcal{F}$, $\Gamma; \bar{\theta} \vdash \tau : \mathcal{F}$ and $*$ be the unique element of $\llbracket \Gamma; \bar{\theta} \vdash \bar{\theta} \rrbracket^{\text{Set}} \rho$. As a special case of the above definition, we have

$$\begin{aligned} & \llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash \text{map}_{\bar{F}}^{\bar{\sigma}, \bar{\tau}} : \text{Nat}^0(\text{Nat}^0 \sigma \tau) (\text{Nat}^0 F[\bar{\alpha} := \bar{\sigma}] F[\bar{\alpha} := \bar{\tau}]) \rrbracket^{\text{Set}} \rho * \\ &= \lambda f : \llbracket \Gamma; \bar{\theta} \vdash \sigma \rrbracket^{\text{Set}} \rho \rightarrow \llbracket \Gamma; \bar{\theta} \vdash \tau \rrbracket^{\text{Set}} \rho. \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \text{id}_{\rho}[\bar{\alpha} := f] \\ &= \lambda f : \llbracket \Gamma; \bar{\theta} \vdash \sigma \rrbracket^{\text{Set}} \rho \rightarrow \llbracket \Gamma; \bar{\theta} \vdash \tau \rrbracket^{\text{Set}} \rho. \text{map}_{\lambda \bar{A}. \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]} \bar{f} \\ &= \text{map}_{\lambda \bar{A}. \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]} \end{aligned}$$

where the first equality is by Equation 12, the second equality is obtained by noting that $\lambda \bar{A}. \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]$ is a functor in α , and map_G denotes the action of the functor G on morphisms.

We also have the expected relationships between interpretations of terms involving map, in, and fold:

- If $\Gamma; \bar{\psi}, \bar{\gamma} \vdash H$, $\Gamma; \bar{\alpha}, \bar{\gamma}, \bar{\phi} \vdash K$, $\Gamma; \bar{\beta}, \bar{\gamma} \vdash F$, and $\Gamma; \bar{\beta}, \bar{\gamma} \vdash G$, then

$$\llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash \text{map}_{H[\bar{\psi} := K]}^{\bar{F}, \bar{G}} : \xi \rrbracket^{\text{Set}} = \llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash \text{map}_H^{K[\bar{\phi} := F], K[\bar{\phi} := G]} \circ \text{map}_K^{\bar{F}, \bar{G}} : \xi \rrbracket^{\text{Set}}$$

at type $\xi = \text{Nat}^0(\text{Nat}^0 \bar{\beta}, \bar{\gamma} F G)(\text{Nat}^0 H[\bar{\psi} := K][\bar{\phi} := F] H[\bar{\psi} := K][\bar{\phi} := G])$

- If $\Gamma; \bar{\beta}, \bar{\gamma} \vdash H$, $\Gamma; \bar{\beta}, \bar{\gamma} \vdash K$, $\Gamma; \bar{\alpha}, \bar{\gamma} \vdash \bar{F}$, $\Gamma; \bar{\alpha}, \bar{\gamma} \vdash \bar{G}$, $\Gamma; \bar{\phi}, \bar{\psi}, \bar{\gamma} \vdash \tau$, \bar{I} is the sequence \bar{F}, H and \bar{J} is the sequence \bar{G}, K then

$$\begin{aligned} & \llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash L_{\bar{\theta}}(x, \bar{y}). L_{\bar{\gamma}} z. x \xrightarrow{\tau[\bar{\psi} := G][\bar{\phi} := K], \bar{\gamma}} \left(((\text{map}_H^{\tau[\bar{\psi} := F][\bar{\phi} := H], \tau[\bar{\psi} := G][\bar{\phi} := K]})_{\bar{\theta}} ((\text{map}_{\tau}^{\bar{I}, \bar{J}})_{\bar{\theta}}(x, \bar{y})) \right)_{\bar{\gamma}} z \rrbracket^{\text{Set}} \\ &= \llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash L_{\bar{\theta}}(x, \bar{y}). L_{\bar{\gamma}} z. ((\text{map}_K^{\tau[\bar{\psi} := F][\bar{\phi} := H], \tau[\bar{\psi} := G][\bar{\phi} := K]})_{\bar{\theta}} ((\text{map}_{\tau}^{\bar{I}, \bar{J}})_{\bar{\theta}}(x, \bar{y})) \rrbracket^{\text{Set}} \end{aligned}$$

at type $\xi = \text{Nat}^0(\text{Nat}^0 \bar{\beta}, \bar{\gamma} H K \times \text{Nat}^0 \bar{\alpha}, \bar{\gamma} F G)(\text{Nat}^0 H[\bar{\beta} := \tau][\bar{\psi} := F][\bar{\phi} := H] K[\bar{\beta} := \tau][\bar{\psi} := G][\bar{\phi} := K])$.

- $\llbracket \Gamma; \bar{\theta} \mid x : \text{Nat}^0 \bar{\beta}, \bar{\gamma} H[\bar{\phi} := F][\bar{\alpha} := \bar{\beta}] F \vdash ((\text{fold}_{H, F})_{\bar{\theta}} x) \circ \text{in}_H : \xi \rrbracket^{\text{Set}}$
 $= \llbracket \Gamma; \bar{\theta} \mid x : \text{Nat}^0 \bar{\beta}, \bar{\gamma} H[\bar{\phi} := F][\bar{\alpha} := \bar{\beta}] F \vdash x \circ ((\text{map}_{H[\bar{\alpha} := \bar{\beta}]}^{(\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}, F})_{\bar{\theta}} ((\text{fold}_{H, F})_{\bar{\theta}} x)) \rrbracket^{\text{Set}}$

at type $\xi = \text{Nat}^0 \bar{\beta}, \bar{\gamma} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}][\bar{\alpha} := \bar{\beta}] F$

- $\llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash \text{in}_H \circ (\text{fold}_{H, H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}]}_{\bar{\theta}} ((\text{map}_H^{H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}][\bar{\alpha} := \bar{\beta}], (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}})_{\bar{\theta}} \text{in}_H)) : \xi \rrbracket^{\text{Set}}$
 $= \llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash \text{Id}_{(\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}} : \xi \rrbracket^{\text{Set}}$

at type $\xi = \text{Nat}^0 \bar{\beta}, \bar{\gamma} (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}$

- $\llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash (\text{fold}_{H, H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}]}_{\bar{\theta}} ((\text{map}_H^{H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}][\bar{\alpha} := \bar{\beta}], (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}})_{\bar{\theta}} \text{in}_H)) \circ \text{in}_H : \xi \rrbracket^{\text{Set}}$
 $= \llbracket \Gamma; \bar{\theta} \mid \bar{\theta} \vdash \text{Id}_{H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}]} : \xi \rrbracket^{\text{Set}}$

at type $\xi = \text{Nat}^0 \bar{\beta}, \bar{\gamma} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}]$.

Analogous results hold for relational interpretations of terms and relational environments. The set and relational interpretations of terms therefore respect the congruence closed equational theory obtained by adding these judgments to those generating the usual congruence closed equational theory induced by the other term formers.

5 FREE THEOREMS FOR NESTED TYPES

5.1 Free Theorems Derived from Naturality

Make this not about *subst* Note that the free theorem for a type is always independent of the particular term of that type, so the proof below is independent of the choice of function *subst*. In addition, it is independent of the particular data type — in this case, *Lam* — over which *subst* acts. Also independent of the functor arguments — in this case $+1$ and *id* — to the data type. Indeed, the following result is just a consequence of naturality.

We already know from Theorem 35 that

$$\begin{aligned} & \llbracket \Gamma; \emptyset \mid x : \text{Nat}^{\bar{\alpha}, \bar{\gamma}} F G, y : \text{Nat}^{\bar{\gamma}} \sigma \tau \vdash ((\text{map}_{\bar{G}}^{\bar{\sigma}, \bar{\tau}})_{\emptyset} \bar{y}) \circ (L_{\bar{\gamma}} z. x_{\bar{\sigma}, \bar{\gamma}} z) : \text{Nat}^{\bar{\gamma}} F[\bar{\alpha} := \bar{\sigma}] G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \\ &= \llbracket \Gamma; \emptyset \mid x : \text{Nat}^{\bar{\alpha}, \bar{\gamma}} F G, y : \text{Nat}^{\bar{\gamma}} \sigma \tau \vdash (L_{\bar{\gamma}} z. x_{\bar{\tau}, \bar{\gamma}} z) \circ ((\text{map}_{\bar{F}}^{\bar{\sigma}, \bar{\tau}})_{\emptyset} \bar{y}) : \text{Nat}^{\bar{\gamma}} F[\bar{\alpha} := \bar{\sigma}] G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \end{aligned} \quad (13)$$

In particular, if we instantiate x with any term *subst* of type $\vdash \text{Nat}^{\alpha}(\text{Lam}(\alpha + 1) \times \text{Lam} \alpha) \text{Lam} \alpha$ (and thus there is a single α and no γ 's) we have

$$\begin{aligned} & \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash ((\text{map}_{\text{Lam} \alpha}^{\sigma, \tau})_{\emptyset} y) \circ (L_{\emptyset} z. \text{subst}_{\sigma} z) : \text{Nat}^0(\text{Lam}(\sigma + 1) \times \text{Lam} \sigma) \text{Lam} \tau \rrbracket^{\text{Set}} \\ &= \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash (L_{\emptyset} z. \text{subst}_{\tau} z) \circ ((\text{map}_{\text{Lam}(\alpha+1) \times \text{Lam} \alpha}^{\sigma, \tau})_{\emptyset} y) : \text{Nat}^0(\text{Lam}(\sigma + 1) \times \text{Lam} \sigma) \text{Lam} \tau \rrbracket^{\text{Set}} \end{aligned} \quad (14)$$

Thus, for any set environment ρ and any function $f : \llbracket \Gamma; \emptyset \vdash \text{Nat}^0 \sigma \tau \rrbracket^{\text{Set}} \rho$, we have that

$$\begin{aligned} & \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash ((\text{map}_{\text{Lam} \alpha}^{\sigma, \tau})_{\emptyset} y) \circ (L_{\emptyset} z. \text{subst}_{\sigma} z) : \text{Nat}^0(\text{Lam}(\sigma + 1) \times \text{Lam} \sigma) \text{Lam} \tau \rrbracket^{\text{Set}} \rho f \\ &= \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash ((\text{map}_{\text{Lam} \alpha}^{\sigma, \tau})_{\emptyset} y) \rrbracket^{\text{Set}} \rho f \circ \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash L_{\emptyset} z. \text{subst}_{\sigma} z \rrbracket^{\text{Set}} \rho f \\ &= \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\text{Lam} \alpha}^{\sigma, \tau} \rrbracket^{\text{Set}} \rho f \circ \llbracket \Gamma; \emptyset \mid \emptyset \vdash L_{\emptyset} z. \text{subst}_{\sigma} z \rrbracket^{\text{Set}} \rho \\ &= \text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} f \circ (\llbracket \vdash \text{subst} \rrbracket^{\text{Set}})_{\llbracket \Gamma; \emptyset \vdash \sigma \rrbracket^{\text{Set}} \rho} \end{aligned} \quad (15)$$

and

$$\begin{aligned} & \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash (L_{\emptyset} z. \text{subst}_{\tau} z) \circ ((\text{map}_{\text{Lam}(\alpha+1) \times \text{Lam} \alpha}^{\sigma, \tau})_{\emptyset} y) : \text{Nat}^0(\text{Lam}(\sigma + 1) \times \text{Lam} \sigma) \text{Lam} \tau \rrbracket^{\text{Set}} \rho f \\ &= \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash L_{\emptyset} z. \text{subst}_{\tau} z \rrbracket^{\text{Set}} \rho f \circ \llbracket \Gamma; \emptyset \mid y : \text{Nat}^0 \sigma \tau \vdash (\text{map}_{\text{Lam}(\alpha+1) \times \text{Lam} \alpha}^{\sigma, \tau})_{\emptyset} y \rrbracket^{\text{Set}} \rho f \\ &= \llbracket \Gamma; \emptyset \mid \emptyset \vdash L_{\emptyset} z. \text{subst}_{\tau} z \rrbracket^{\text{Set}} \rho \circ \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\text{Lam}(\alpha+1) \times \text{Lam} \alpha}^{\sigma, \tau} \rrbracket^{\text{Set}} \rho f \\ &= (\llbracket \vdash \text{subst} \rrbracket^{\text{Set}})_{\llbracket \Gamma; \emptyset \vdash \tau \rrbracket^{\text{Set}} \rho} \circ \text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam}(\alpha+1) \times \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} f \\ &= (\llbracket \vdash \text{subst} \rrbracket^{\text{Set}})_{\llbracket \Gamma; \emptyset \vdash \tau \rrbracket^{\text{Set}} \rho} \circ (\text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} (f + 1) \times \text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} f) \end{aligned} \quad (16)$$

So, we can conclude that

$$\begin{aligned} & \text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} f \circ (\llbracket \vdash \text{subst} \rrbracket^{\text{Set}})_{\llbracket \Gamma; \emptyset \vdash \sigma \rrbracket^{\text{Set}} \rho} \\ &= (\llbracket \vdash \text{subst} \rrbracket^{\text{Set}})_{\llbracket \Gamma; \emptyset \vdash \tau \rrbracket^{\text{Set}} \rho} \circ (\text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} (f + 1) \times \text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} f) \end{aligned} \quad (17)$$

Moreover, for any $A, B : \text{Set}$, we can choose $\sigma = v$ and $\tau = w$ to be variables such that $\rho v = A$ and $\rho w = B$. Then for any function $f : A \rightarrow B$ we have that

$$\begin{aligned} & \text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} f \circ (\llbracket \vdash \text{subst} \rrbracket^{\text{Set}})_A \\ &= (\llbracket \vdash \text{subst} \rrbracket^{\text{Set}})_B \circ (\text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} (f + 1) \times \text{map}_{\llbracket \emptyset; \alpha \vdash \text{Lam} \alpha \rrbracket^{\text{Set}}[\alpha := _]} f) \end{aligned} \quad (18)$$

5.2 The Abstraction Theorem

To go beyond naturality and get *all* consequences of parametricity, we prove an Abstraction Theorem for our calculus. In fact, we actually prove a more general result in Theorem 36 about possibly open terms. We then recover the Abstraction Theorem as the special case of Theorem 36 for closed terms of closed type.

THEOREM 36. *Every well-formed term $\Gamma; \Phi \mid \Delta \vdash t : \tau$ induces a natural transformation from $\llbracket \Gamma; \Phi \vdash \Delta \rrbracket$ to $\llbracket \Gamma; \Phi \vdash \tau \rrbracket$, i.e., a triple of natural transformations*

$$(\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}}, \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}}, \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}})$$

where

$$\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} : \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rightarrow \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}$$

has as its component at $\rho : \text{SetEnv}$ a morphism

$$\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}} \rho : \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho \rightarrow \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho$$

in Set , and

$$\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} : \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rightarrow \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}}$$

has as its component at $\rho : \text{RelEnv}$ a morphism

$$\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho : \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rho \rightarrow \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho$$

in Rel , and for all $\rho : \text{RelEnv}$,

$$\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Rel}} \rho = (\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}}(\pi_1 \rho), \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}}(\pi_2 \rho))$$

PROOF. We proceed by structural induction, showing only the interesting cases.

- We first consider $\Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G$.

– To see that $\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}$ is a natural transformation from $\llbracket \Gamma; \emptyset \vdash \Delta \rrbracket^{\text{Set}}$ to $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}$, since the functorial part Φ of the context is empty, we need only show that, for every $\rho : \text{SetEnv}$, $\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho$ is a morphism in Set from $\llbracket \Gamma; \emptyset \vdash \Delta \rrbracket^{\text{Set}} \rho$ to $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho$. For this, recall that

$$\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho = \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _])$$

By the induction hypothesis, $\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _]$ induces a natural transformation

$$\begin{aligned} & \llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \\ & : \llbracket \Gamma; \bar{\alpha} \vdash \Delta, x : F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \\ & = \llbracket \Gamma; \bar{\alpha} \vdash \Delta \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \times \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \end{aligned}$$

and thus a family of morphisms

$$\begin{aligned} & \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _]) \\ & : \llbracket \Gamma; \bar{\alpha} \vdash \Delta \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \rightarrow (\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _]) \end{aligned}$$

That is, for each $\bar{A} : \text{Set}$ and each $d : \llbracket \Gamma; \emptyset \vdash \Delta \rrbracket^{\text{Set}} \rho = \llbracket \Gamma; \bar{\alpha} \vdash \Delta \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]$ by weakening, we have

$$\begin{aligned} & (\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho d)_{\bar{A}} \\ & = \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]) d \\ & : \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}] \end{aligned}$$

Moreover, these maps actually form a natural transformation $\eta : \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _]$ because each

$$\eta_{\bar{A}} = \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]) d$$

is the component at \bar{A} of the partial specialization to d of the natural transformation $\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _]$.

To see that the components of η also satisfy the additional condition necessary for η to be in $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho$, let $R : \text{Rel}(A, B)$ and

$$(u, v) \in \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}] = (\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}], \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{B}])$$

Then the induction hypothesis on the term t ensures that

$$\begin{aligned} & \llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}] \\ & : \llbracket \Gamma; \bar{\alpha} \vdash \Delta, x : F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}] \end{aligned}$$

and

$$\begin{aligned} & \llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}] \\ & = (\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}], \llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{B}]) \quad (*) \end{aligned}$$

Since $(d, d) \in \llbracket \Gamma; \emptyset \vdash \Delta \rrbracket^{\text{Rel}} \text{Eq}_\rho = \llbracket \Gamma; \emptyset \vdash \Delta \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}]$ we therefore have that

$$\begin{aligned} & (\eta_{\bar{A}} u, \eta_{\bar{B}} v) \\ & = (\text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{A}]) d u, \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \bar{B}]) d v) \\ & = \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}]) (d, d) (u, v) \\ & : \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\alpha} := \bar{R}] \end{aligned}$$

Here, the second equality is by $(*)$.

- The proofs that $\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}}$ is a natural transformation from $\llbracket \Gamma; \emptyset \vdash \Delta \rrbracket^{\text{Rel}}$ to $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}}$ and that, for all $\rho : \text{RelEnv}$ and $d : \llbracket \Gamma; \emptyset \vdash \Delta \rrbracket^{\text{Rel}}$,

$$\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho d$$

is a natural transformation from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := _]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := _]$, are analogous.

- Finally, to see that $\pi_i(\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho) = \llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} (\pi_i \rho)$ we observe that π_1 and π_2 are surjective and compute

$$\begin{aligned} & \pi_i(\llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho) \\ & = \pi_i(\text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := _])) \\ & = \text{curry}(\pi_i(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Rel}} \rho[\bar{\alpha} := _])) \\ & = \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} (\pi_i(\rho[\bar{\alpha} := _]))) \\ & = \text{curry}(\llbracket \Gamma; \bar{\alpha} \mid \Delta, x : F \vdash t : G \rrbracket^{\text{Set}} (\pi_i \rho)[\bar{\alpha} := _])) \\ & = \llbracket \Gamma; \emptyset \mid \Delta \vdash L_{\bar{\alpha}} x.t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} (\pi_i \rho) \end{aligned}$$

- We now consider $\Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}]$.

- To see that $\llbracket \Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}$ is a natural transformation from $\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}}$ to $\llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}$ we need to show that, for every $\rho : \text{SetEnv}$, $\llbracket \Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho$ is a morphism from $\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho$ to $\llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho$, and that this family of morphisms is natural in ρ . Let $d : \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho$. Then

$$\begin{aligned} & \llbracket \Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho d \\ & = (\text{eval} \circ \langle \langle \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho _ \rangle_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}, \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho \rangle) d \\ & = \text{eval}((\llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho _ \rangle_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} d, \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho d) \\ & = \text{eval}((\llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho d \rangle_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}, \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho d) \end{aligned}$$

By the induction hypothesis, $(\llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho d)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}$ has type

$$\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \rightarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho]$$

and $\llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho d$ has type

$$\begin{aligned} & \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho \\ &= \llbracket \Gamma; \Phi, \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \\ &= \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \end{aligned}$$

by Equation 4, and by weakening in the last step, since the type $\Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G$ is only well-formed if $\Gamma; \bar{\alpha} \vdash F : \mathcal{F}$ and $\Gamma; \bar{\alpha} \vdash G : \mathcal{F}$. Thus, $\llbracket \Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho d$ has type $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] = \llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho$, as desired.

To see that the family of maps comprising $\llbracket \Gamma; \Phi \mid \Delta \vdash t_{\bar{\tau}} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}$ form a natural transformation, i.e., are natural in their set environment argument, we need to show that the following diagram commutes:

$$\begin{array}{ccc} \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho & \xrightarrow{\llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} f} & \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Set}} \rho' \\ \downarrow \langle \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho, \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho \rangle & \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} f \times \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f & \downarrow \langle \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho', \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho' \rangle \\ \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho \times \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho & \xrightarrow{\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} f \times \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f} & \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho' \times \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho' \\ \downarrow \text{eval} \circ ((-)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} \times id) & & \downarrow \text{eval} \circ ((-)_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'} \\ \llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho & \xrightarrow{\llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f} & \llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho' \end{array}$$

The top diagram commutes because the induction hypothesis ensures $\llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}$ and $\llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}$ are natural in ρ . To see that the bottom diagram commutes, we first note that since $\rho \upharpoonright_{\Gamma} = \rho' \upharpoonright_{\Gamma}$, $\Gamma; \bar{\alpha} \vdash F : \mathcal{F}$, and $\Gamma; \bar{\alpha} \vdash G : \mathcal{F}$ we can replace the instance of f in $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} f$ with id . Then, using the fact that $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}$ is a functor, we have that $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} id = id$. To see that the bottom diagram commutes we must therefore prove that, for every $\eta \in \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho$ and $x \in \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho$, we have

$$\llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f(\eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} x) = \eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'}(\llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f x)$$

i.e., that for every $\eta \in \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho$,

$$\llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f \circ \eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} = \eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'} \circ \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f$$

But this follows from the naturality of η . Indeed, $\eta \in \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}} \rho$ implies that η is a natural transformation from $\llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _]$ to $\llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := _]$. For each τ , consider the morphism $\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f : \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho \rightarrow \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'$. The following

diagram commutes by naturality of η :

$$\begin{array}{ccc}
 \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho & & \llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \rho \\
 \parallel & & \parallel \\
 \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] & \xrightarrow{\eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho}} & \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho] \\
 \downarrow \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f]} & & \downarrow \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} id_{\rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f]} \\
 \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'] & \xrightarrow{\eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'}} & \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} \rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho']
 \end{array}$$

That is,

$$\begin{aligned}
 & \llbracket \Gamma; \bar{\alpha} \vdash G \rrbracket^{\text{Set}} id_{\rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f]} \circ \eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} \\
 = & \eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'} \circ \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f]}
 \end{aligned}$$

But since the only variables in the functorial contexts for F and G are $\bar{\alpha}$, we have that

$$\begin{aligned}
 & \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f]} \\
 = & \llbracket \Gamma; \bar{\alpha} \vdash F \rrbracket^{\text{Set}} f[\bar{\alpha} := \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} f] \\
 = & \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f
 \end{aligned}$$

and similarly for G . Commutativity of this last diagram thus gives that $\llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f \circ \eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho} = \eta_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho'} \circ \llbracket \Gamma; \Phi \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} f$, as desired.

- The proof that $\llbracket \Gamma; \Phi \mid \Delta \vdash t_{\tau} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}}$ is a natural transformation from $\llbracket \Gamma; \Phi \mid \Delta \rrbracket^{\text{Rel}}$ to $\llbracket \Gamma; \Phi \vdash G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}}$ is analogous.
- Finally, to see that $\pi_i(\llbracket \Gamma; \Phi \mid \Delta \vdash t_{\tau} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}} \rho) = \llbracket \Gamma; \Phi \mid \Delta \vdash t_{\tau} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}(\pi_i \rho)$ we compute

$$\begin{aligned}
 & \pi_i(\llbracket \Gamma; \Phi \mid \Delta \vdash t_{\tau} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}} \rho) \\
 = & \pi_i(\text{eval} \circ \langle \langle \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho _ \rangle_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho}, \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}} \rho \rangle) \\
 = & \text{eval} \circ \langle \pi_i(\langle \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho _ \rangle_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho}), \pi_i(\llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}} \rho) \rangle \\
 = & \text{eval} \circ \langle \pi_i(\llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Rel}} \rho _ \rangle_{\pi_i(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho)}, \pi_i(\llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Rel}} \rho) \rangle \\
 = & \text{eval} \circ \langle \langle \llbracket \Gamma; \emptyset \mid \Delta \vdash t : \text{Nat}^{\bar{\alpha}} F G \rrbracket^{\text{Set}}(\pi_i \rho) _ \rangle_{\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_i \rho)}, \llbracket \Gamma; \Phi \mid \Delta \vdash s : F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}(\pi_i \rho) \rangle \\
 = & \llbracket \Gamma; \Phi \mid \Delta \vdash t_{\tau} s : G[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}}(\pi_i \rho)
 \end{aligned}$$

- We now consider $\Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\bar{H}}^{\bar{F}, \bar{G}} : \text{Nat}^{\emptyset}(\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}])$.

- To see that $\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\bar{H}}^{\bar{F}, \bar{G}} : \text{Nat}^{\emptyset}(\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Set}}$ is a natural transformation from $\llbracket \Gamma; \emptyset \mid \emptyset \rrbracket^{\text{Set}}$ to $\llbracket \text{Nat}^{\emptyset}(\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Set}}$, since the functorial part Φ of the context is empty, we need only show that, for every $\rho : \text{SetEnv}$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\bar{H}}^{\bar{F}, \bar{G}} : \text{Nat}^{\emptyset}(\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Set}} \rho$$

is a morphism in Set from $\llbracket \Gamma; \emptyset \mid \emptyset \rrbracket^{\text{Set}} \rho$ to

$$\llbracket \Gamma; \emptyset \mid \text{Nat}^{\emptyset}(\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Set}} \rho$$

i.e., that, for the unique $d : \llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Set}} \rho$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\overline{H}}^{\overline{F}, \overline{G}} : \text{Nat}^0 (\text{Nat}^{\overline{\beta}, \overline{\gamma}} F G) (\text{Nat}^{\overline{\gamma}} H[\overline{\phi} :=_{\overline{\beta}} F] H[\overline{\phi} :=_{\overline{\beta}} G]) \rrbracket^{\text{Set}} \rho d$$

is a morphism from $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\overline{\beta}, \overline{\gamma}} F G \rrbracket^{\text{Set}} \rho$ to $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\overline{\gamma}} H[\overline{\phi} :=_{\overline{\beta}} F] H[\overline{\phi} :=_{\overline{\beta}} G] \rrbracket^{\text{Set}} \rho$.

For this we show that for all $\eta : \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\overline{\beta}, \overline{\gamma}} F G \rrbracket^{\text{Set}} \rho$ we have

$$\begin{aligned} & \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\overline{H}}^{\overline{F}, \overline{G}} : \text{Nat}^0 (\text{Nat}^{\overline{\beta}, \overline{\gamma}} F G) (\text{Nat}^{\overline{\gamma}} H[\overline{\phi} :=_{\overline{\beta}} F] H[\overline{\phi} :=_{\overline{\beta}} G]) \rrbracket^{\text{Set}} \rho d \bar{\eta} \\ & : \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\overline{\gamma}} H[\overline{\phi} :=_{\overline{\beta}} F] H[\overline{\phi} :=_{\overline{\beta}} G] \rrbracket^{\text{Set}} \rho \end{aligned}$$

To this end, we note that, for any \bar{B} ,

$$\begin{aligned} & (\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\overline{H}}^{\overline{F}, \overline{G}} : \text{Nat}^0 (\text{Nat}^{\overline{\beta}, \overline{\gamma}} F G) (\text{Nat}^{\overline{\gamma}} H[\overline{\phi} :=_{\overline{\beta}} F] H[\overline{\phi} :=_{\overline{\beta}} G]) \rrbracket^{\text{Set}} \rho d \bar{\eta})_{\bar{B}} \\ = & \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{\rho[\overline{\gamma} := \bar{B}]} [\phi := \lambda \bar{A}. \eta_{\bar{A} \bar{B}}] \end{aligned}$$

is indeed a morphism from

$$\begin{aligned} & \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := F] \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] \\ = & \llbracket \Gamma; \bar{\gamma}, \bar{\phi} \vdash H \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] [\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] [\beta := A]] \end{aligned}$$

to

$$\begin{aligned} & \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := G] \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] \\ = & \llbracket \Gamma; \bar{\gamma}, \bar{\phi} \vdash H \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] [\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash G \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] [\beta := A]] \end{aligned}$$

since $\llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}}$ is a functor from SetEnv to Set and $id_{\rho[\overline{\gamma} := \bar{B}]} [\phi := \lambda \bar{A}. \eta_{\bar{A} \bar{B}}]$ is a morphism in SetEnv from

$$\rho[\overline{\gamma} := \bar{B}] [\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] [\beta := A]]$$

to

$$\rho[\overline{\gamma} := \bar{B}] [\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash G \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] [\beta := A]]$$

To see that this family of morphisms is natural in \bar{B} we first observe that if $f : B \rightarrow B'$ then, writing t for $\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{\overline{H}}^{\overline{F}, \overline{G}} : \text{Nat}^0 (\text{Nat}^{\overline{\beta}, \overline{\gamma}} F G) (\text{Nat}^{\overline{\gamma}} H[\overline{\phi} :=_{\overline{\beta}} F] H[\overline{\phi} :=_{\overline{\beta}} G]) \rrbracket^{\text{Set}} \rho d \bar{\eta}$, we have

$$\begin{array}{ccc} \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := F] \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] & \xrightarrow{t_{\bar{B}}} & \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := G] \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] \\ \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := F] \rrbracket^{\text{Set}} id_{\rho[\overline{\gamma} := f]} \downarrow & & \downarrow \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := G] \rrbracket^{\text{Set}} id_{\rho[\overline{\gamma} := f]} \\ \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := F] \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}'] & \xrightarrow{t_{\bar{B}'}} & \llbracket \Gamma; \bar{\gamma} \vdash H[\overline{\phi} := G] \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}'] \end{array}$$

This diagram commutes because $\llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}}$ is a functor from SetEnv to Set and because, letting

$$E_{F, B} = \rho[\overline{\gamma} := \bar{B}] [\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Set}} \rho[\overline{\gamma} := \bar{B}] [\beta := A]]$$

and

$$e_{F, f} = id_{\rho[\overline{\gamma} := f]} [\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Set}} \rho[\overline{\gamma} := f] [\beta := id_A]]$$

for all F and B and $\bar{f} : B \rightarrow B'$, the following diagram commutes by the fact that composition of environments is componentwise together with the naturality of η :

$$\begin{array}{ccc}
 E_{F,B} & \xrightarrow{id_\rho[\gamma := id_B][\phi := \lambda \bar{A}. \eta_{\bar{A} \bar{B}}]} & E_{G,B} \\
 \downarrow e_{F,f} & & \downarrow e_{G,f} \\
 E_{F,B'} & \xrightarrow{id_\rho[\gamma := id_{B'}][\phi := \lambda \bar{A}. \eta_{\bar{A} \bar{B}'}]} & E_{G,B'}
 \end{array}$$

We therefore have that

$$\lambda \bar{B}. \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F}, \bar{G}}}^{\bar{F}, \bar{G}} : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Set}} \rho d \bar{\eta} \bar{B}$$

is natural in \bar{B} as desired.

– To see that, for every $\rho : \text{SetEnv}$ and $d : \llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Set}} \rho$, and all $\eta : \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} F G \rrbracket^{\text{Set}} \rho$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F}, \bar{G}}}^{\bar{F}, \bar{G}} : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Set}} \rho d \bar{\eta}$$

satisfies the additional condition necessary for it to be in $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}] \rrbracket^{\text{Set}} \rho$,

let $\bar{R} : \text{Rel}(B, B')$ and $\bar{S} : \text{Rel}(C, C')$. Since each map in $\bar{\eta}$ satisfies the extra condition necessary for it to be in its corresponding $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} F G \rrbracket^{\text{Set}} \rho$ – i.e., since

$$(\eta_{\bar{B} \bar{C}}, \eta_{\bar{B}' \bar{C}'}) \in \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\beta} := \bar{R}][\bar{\gamma} := \bar{S}] \rightarrow \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash G \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\beta} := \bar{R}][\bar{\gamma} := \bar{S}]$$

– we have that

$$\begin{aligned}
 & ((\lambda e \nu \bar{Z}. \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{\rho[\bar{\gamma} := \bar{Z}]}[\bar{\phi} := \lambda \bar{A}. \nu_{\bar{A} \bar{Z}}]) d \bar{\eta} \bar{B}, \\
 & (\lambda e \nu \bar{Z}. \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{\rho[\bar{\gamma} := \bar{Z}]}[\bar{\phi} := \lambda \bar{A}. \nu_{\bar{A} \bar{Z}}]) d \bar{\eta} \bar{B}') \\
 = & (\llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{\rho[\bar{\gamma} := B]}[\bar{\phi} := \lambda \bar{A}. \eta_{\bar{A} \bar{B}}], \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{\rho[\bar{\gamma} := B']}[\bar{\phi} := \lambda \bar{A}. \eta_{\bar{A} \bar{B}'}])
 \end{aligned}$$

has type

$$\begin{aligned}
 & (\llbracket \Gamma; \bar{\gamma} \vdash H[\bar{\phi} := \bar{F}] \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{B}] \rightarrow \llbracket \Gamma; \bar{\gamma} \vdash H[\bar{\phi} := \bar{G}] \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{B}], \\
 & \llbracket \Gamma; \bar{\gamma} \vdash H[\bar{\phi} := \bar{F}] \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{B}'] \rightarrow \llbracket \Gamma; \bar{\gamma} \vdash H[\bar{\phi} := \bar{G}] \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{B}']) \\
 = & \llbracket \Gamma; \bar{\gamma} \vdash H[\bar{\phi} := \bar{F}] \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{R}] \rightarrow \llbracket \Gamma; \bar{\gamma} \vdash H[\bar{\phi} := \bar{G}] \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{R}]
 \end{aligned}$$

as desired.

– The proofs that

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F}, \bar{G}}}^{\bar{F}, \bar{G}} : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Rel}}$$

is a natural transformation from $\llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Rel}}$ to

$$\llbracket \Gamma; \emptyset \vdash \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Rel}}$$

and that, for every $\rho : \text{RelEnv}$ and the unique $d : \llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Rel}} \rho$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F}, \bar{G}}}^{\bar{F}, \bar{G}} : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} \bar{F}] H[\bar{\phi} :=_{\bar{\beta}} \bar{G}]) \rrbracket^{\text{Rel}} \rho d$$

is a morphism from $\overline{\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} F G \rrbracket^{\text{Rel}} \rho}$ to $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} F] H[\bar{\phi} :=_{\bar{\beta}} G] \rrbracket^{\text{Rel}} \rho$,
are analogous.

– Finally, to see that

$$\begin{aligned} & \pi_i(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F} \bar{G}}}^{\bar{F} \bar{G}} : \text{Nat}^{\emptyset}(\overline{\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G}) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} F] H[\bar{\phi} :=_{\bar{\beta}} G]) \rrbracket^{\text{Rel}} \rho) \\ = & \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F} \bar{G}}}^{\bar{F} \bar{G}} : \text{Nat}^{\emptyset}(\overline{\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G}) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} F] H[\bar{\phi} :=_{\bar{\beta}} G]) \rrbracket^{\text{Set}} (\pi_i \rho) \end{aligned}$$

we compute

$$\begin{aligned} & \pi_i(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F} \bar{G}}}^{\bar{F} \bar{G}} : \text{Nat}^{\emptyset}(\overline{\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G}) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} F] H[\bar{\phi} :=_{\bar{\beta}} G]) \rrbracket^{\text{Rel}} \rho) \\ = & \pi_i(\lambda e \bar{v} \bar{R}. \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Rel}} id_{\rho[\bar{\gamma} := \bar{R}]}[\bar{\phi} := \lambda \bar{S}. v_{\bar{S}} \bar{R}]) \\ = & \lambda e \bar{v} \bar{R}. \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{(\pi_i \rho)[\bar{\gamma} := \pi_i \bar{R}]}[\bar{\phi} := \lambda \bar{S}. (\pi_i v)_{\pi_i \bar{S} \pi_i \bar{R}}] \\ = & \lambda d \bar{\eta} \bar{B}. \llbracket \Gamma; \bar{\phi}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} id_{(\pi_i \rho)[\bar{\gamma} := \bar{B}]}[\bar{\phi} := \lambda \bar{A}. \eta_{\bar{A} \bar{B}}] \\ = & \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{map}_{H^{\bar{F} \bar{G}}}^{\bar{F} \bar{G}} : \text{Nat}^{\emptyset}(\overline{\text{Nat}^{\bar{\beta}, \bar{\gamma}} F G}) (\text{Nat}^{\bar{\gamma}} H[\bar{\phi} :=_{\bar{\beta}} F] H[\bar{\phi} :=_{\bar{\beta}} G]) \rrbracket^{\text{Set}} (\pi_i \rho) \end{aligned}$$

- We now consider $\Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\bar{\alpha} := \bar{\beta}] (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}$.
– To see that if $d : \llbracket \Gamma; \emptyset \mid \emptyset \rrbracket^{\text{Set}} \rho$ then

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\bar{\alpha} := \bar{\beta}] (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho d$$

is in $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\bar{\alpha} := \bar{\beta}] (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho$, we first note that, for all \bar{B} and \bar{C} ,

$$\begin{aligned} & (\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\bar{\alpha} := \bar{\beta}] (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho d)_{\bar{B} \bar{C}} \\ = & (in_{T_{\rho[\bar{\gamma} := \bar{C}]}})_{\bar{B}} \end{aligned}$$

does indeed map

$$\begin{aligned} & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}] [\bar{\gamma} := \bar{C}] \\ = & \llbracket \Gamma; \bar{\beta}, \bar{\gamma}, \bar{\alpha} \vdash H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}] [\bar{\gamma} := \bar{C}] [\bar{\alpha} := \bar{B}] \\ = & \llbracket \Gamma; \bar{\phi}, \bar{\beta}, \bar{\gamma}, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}] [\bar{\gamma} := \bar{C}] [\bar{\alpha} := \bar{B}] \\ & [\bar{\phi} := \lambda \bar{D}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma}, \bar{\alpha} \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}] [\bar{\gamma} := \bar{C}] [\bar{\alpha} := \bar{B}] [\bar{\beta} := \bar{D}]] \\ = & \llbracket \Gamma; \bar{\phi}, \bar{\gamma}, \bar{\alpha} \vdash H \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{C}] [\bar{\alpha} := \bar{B}] \\ & [\bar{\phi} := \lambda \bar{D}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{D}] [\bar{\gamma} := \bar{C}]] \\ = & T_{\rho[\bar{\gamma} := \bar{C}]}(\lambda \bar{D}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{D}] [\bar{\gamma} := \bar{C}]) \bar{B} \\ = & T_{\rho[\bar{\gamma} := \bar{C}]}(\mu T_{\rho[\bar{\gamma} := \bar{C}]}) \bar{B} \end{aligned}$$

to

$$\begin{aligned} & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}] [\bar{\gamma} := \bar{C}] \\ = & (\lambda \bar{D}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{D}] [\bar{\gamma} := \bar{C}]) \bar{B} \\ = & (\mu T_{\rho[\bar{\gamma} := \bar{C}]}) \bar{B} \end{aligned}$$

To see that

$$\begin{aligned} & \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\bar{\phi} := (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta}] [\bar{\alpha} := \bar{\beta}] (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho d \\ = & \lambda \bar{B} \bar{C}. (in_{T_{\rho[\bar{\gamma} := \bar{C}]}})_{\bar{B}} \end{aligned}$$

is natural in \bar{B} and \bar{C} , we observe that the following diagram commutes for all $\bar{f} : \bar{B} \rightarrow \bar{B}'$ and $\bar{g} : \bar{C} \rightarrow \bar{C}'$:

$$\begin{array}{ccc}
 T_{\rho[\bar{Y}:=\bar{C}]} (\mu T_{\rho[\bar{Y}:=\bar{C}]}) \bar{B} & \xrightarrow{(in_{T_{\rho[\bar{Y}:=\bar{C}]}})_{\bar{B}}} & (\mu T_{\rho[\bar{Y}:=\bar{C}]}) \bar{B} \\
 \downarrow \sigma_{id_{\rho}[\bar{Y}:=\bar{g}]} (\mu \sigma_{id_{\rho}[\bar{Y}:=\bar{g}]}) \bar{B} & & \downarrow (\mu \sigma_{id_{\rho}[\bar{Y}:=\bar{g}]}) \bar{B} \\
 T_{\rho[\bar{Y}:=\bar{C}']} (\mu T_{\rho[\bar{Y}:=\bar{C}']}) \bar{B} & \xrightarrow{(in_{T_{\rho[\bar{Y}:=\bar{C}']}})_{\bar{B}}} & (\mu T_{\rho[\bar{Y}:=\bar{C}']}) \bar{B} \\
 \downarrow T_{\rho[\bar{Y}:=\bar{C}']} (\mu T_{\rho[\bar{Y}:=\bar{C}']}) \bar{f} & & \downarrow (in_{T_{\rho[\bar{Y}:=\bar{C}']}})_{\bar{B}} \\
 T_{\rho[\bar{Y}:=\bar{C}']} (\mu T_{\rho[\bar{Y}:=\bar{C}']}) \bar{B}' & \xrightarrow{(in_{T_{\rho[\bar{Y}:=\bar{C}']}})_{\bar{B}'}} & (\mu T_{\rho[\bar{Y}:=\bar{C}']}) \bar{B}'
 \end{array}$$

Indeed, naturality of in with respect to its functor argument ensures that the top diagram commutes, and naturality of $in_{T_{\rho[\bar{Y}:=\bar{C}]}}$ ensures that the bottom one commutes.

- To see that $\llbracket \Gamma; \emptyset \mid \emptyset \vdash in_H : Nat^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} \rho d$ satisfies the additional property necessary for it to be in

$$\llbracket \Gamma; \emptyset \vdash Nat^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} \rho$$

let $\bar{R} : \text{Rel}(\bar{B}, \bar{B}')$ and $\bar{S} : \text{Rel}(\bar{C}, \bar{C}')$. Then

$$\begin{aligned}
 & ((\llbracket \Gamma; \emptyset \mid \emptyset \vdash in_H : Nat^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} \rho d)_{\bar{B}, \bar{C}}, \\
 & (\llbracket \Gamma; \emptyset \mid \emptyset \vdash in_H : Nat^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} \rho d)_{\bar{B}', \bar{C}'} \\
 = & ((in_{T_{\rho[\bar{Y}:=\bar{C}]}})_{\bar{B}}, (in_{T_{\rho[\bar{Y}:=\bar{C}']}})_{\bar{B}'})
 \end{aligned}$$

has type

$$\begin{aligned}
 & (\llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}] \rightarrow \\
 & \quad \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}], \\
 & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}'][\bar{\gamma} := \bar{C}'] \rightarrow \\
 & \quad \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}'][\bar{\gamma} := \bar{C}']) \\
 = & (T_{\rho[\bar{Y}:=\bar{C}]} (\mu T_{\rho[\bar{Y}:=\bar{C}]}) \bar{B} \rightarrow (\mu T_{\rho[\bar{Y}:=\bar{C}]}) \bar{B}, T_{\rho[\bar{Y}:=\bar{C}']} (\mu T_{\rho[\bar{Y}:=\bar{C}']}) \bar{B}' \rightarrow (\mu T_{\rho[\bar{Y}:=\bar{C}']}) \bar{B}') \\
 = & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Rel}} \text{Eq}_{\rho}[\bar{\beta} := \bar{R}][\bar{\gamma} := \bar{S}] \rightarrow \\
 & \quad \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Rel}} \text{Eq}_{\rho}[\bar{\beta} := \bar{R}][\bar{\gamma} := \bar{S}]
 \end{aligned}$$

- The proofs that $\llbracket \Gamma; \emptyset \mid \emptyset \vdash in_H : Nat^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Rel}}$ is a natural transformation from $\llbracket \Gamma; \emptyset \mid \emptyset \rrbracket^{\text{Rel}}$ to $\llbracket \Gamma; \emptyset \vdash Nat^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Rel}}$ and that, for all $\rho : \text{RelEnv}$ and $d : \llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Rel}}$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash in_H : Nat^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Rel}} \rho d$$

is a natural transformation from $\lambda \bar{R} \bar{S}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Rel}} \rho[\bar{\beta} := \bar{R}][\bar{\gamma} := \bar{S}]$ to $\lambda \bar{R} \bar{S}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Rel}} \rho[\bar{\beta} := \bar{R}][\bar{\gamma} := \bar{S}]$, are analogous.

- Finally, to see that $\pi_i(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Rel}} \rho d) = \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} (\pi_i \rho) (\pi_i d)$ we first note that $d : \llbracket \Gamma; \emptyset \mid \emptyset \rrbracket^{\text{Rel}} \rho$ and $\pi_i d : \llbracket \Gamma; \emptyset \mid \emptyset \rrbracket^{\text{Set}} (\pi_i \rho)$ are uniquely determined. Further, the definition of natural transformations in Rel ensures that, for any \bar{R} and \bar{S} ,

$$\begin{aligned} & (in_{T_{\rho[\bar{Y} := \bar{S}]}})_{\bar{R}} \\ &= ((in_{\pi_1(T_{\rho[\bar{Y} := \bar{S}]})})_{\pi_1 \bar{R}}, (in_{\pi_2(T_{\rho[\bar{Y} := \bar{S}]})})_{\pi_2 \bar{R}}) \\ &= ((in_{T_{\rho[\bar{Y} := \pi_1 \bar{S}]}}^{\text{Set}})_{\pi_1 \bar{R}}, (in_{T_{\rho[\bar{Y} := \pi_2 \bar{S}]}}^{\text{Set}})_{\pi_2 \bar{R}}) \end{aligned}$$

Observing that π_1 and π_2 are surjective, we therefore have that

$$\begin{aligned} & \pi_i(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Rel}} \rho d) \\ &= \pi_i(\lambda \bar{R} \bar{S}. (in_{T_{\rho[\bar{Y} := \bar{S}]}})_{\bar{R}}) \\ &= \lambda \bar{B} \bar{C}. (in_{T_{\rho[\bar{Y} := \bar{C}]}}^{\text{Set}})_{\bar{B}} \\ &= \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{in}_H : \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta}][\bar{\alpha} := \bar{\beta}] (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} (\pi_i \rho) (\pi_i d) \end{aligned}$$

- We now consider $\Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F)$.
– To see that $\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F) \rrbracket^{\text{Set}}$ is a natural transformation from $\llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Set}}$ to

$$\llbracket \Gamma; \emptyset \vdash \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F) \rrbracket^{\text{Set}}$$

since the functorial part Φ of the context is empty, we need only show that, for every $\rho : \text{SetEnv}$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F) \rrbracket^{\text{Set}} \rho$$

is a morphism in Set from $\llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Set}} \rho$ to

$$\llbracket \Gamma; \emptyset \vdash \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F) \rrbracket^{\text{Set}} \rho$$

i.e., that, for the unique $d : \llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Set}} \rho$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F) \rrbracket^{\text{Set}} \rho d$$

is a morphism from $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F \rrbracket^{\text{Set}} \rho$ to $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F \rrbracket^{\text{Set}} \rho$.

For this we show that for every $\eta : \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F \rrbracket^{\text{Set}} \rho$ we have

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F) \rrbracket^{\text{Set}} \rho d \eta$$

$$: \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F \rrbracket^{\text{Set}} \rho$$

To this end we show that, for any \bar{B} and \bar{C} ,

$$(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} F) \rrbracket^{\text{Set}} \rho d \eta)_{\bar{B} \bar{C}}$$

is a morphism from

$$\llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu\phi.\lambda\bar{\alpha}.H)\bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}] = (\mu T_{\rho[\bar{\gamma} := \bar{C}]}^{\text{Set}})_{\bar{B}}$$

to

$$\llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}]$$

To see this, we use Equations 4 and 6 for the first and second equalities below, together with weakening, to see that η is itself a natural transformation from

$$\begin{aligned}
 & \lambda \bar{B} \bar{C}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\phi := F][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}] \\
 = & \lambda \bar{B} \bar{C}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma}, \bar{\alpha} \vdash H[\phi := F] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}][\bar{\alpha} := \bar{B}] \\
 = & \lambda \bar{B} \bar{C}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma}, \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}][\bar{\alpha} := \bar{B}] \\
 & [\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma}, \bar{\alpha} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}][\bar{\alpha} := \bar{B}][\bar{\beta} := \bar{A}]] \\
 = & \lambda \bar{B} \bar{C}. \llbracket \Gamma; \bar{\gamma}, \bar{\alpha}, \phi \vdash H \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{C}][\bar{\alpha} := \bar{B}][\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{C}][\bar{\beta} := \bar{A}]] \\
 = & \lambda \bar{B} \bar{C}. T_{\rho[\bar{\gamma} := \bar{C}]}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{A}][\bar{\gamma} := \bar{C}]) \bar{B}
 \end{aligned}$$

to

$$\lambda \bar{B} \bar{C}. (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{A}][\bar{\gamma} := \bar{C}]) \bar{B} = \lambda \bar{B} \bar{C}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}]$$

Thus, if $x : \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}] = (\mu T_{\rho[\bar{\gamma} := \bar{C}]}^{\text{Set}}) \bar{B}$, then

$$\begin{aligned}
 & (\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := \bar{\beta} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Set}} \rho d \eta)_{\bar{B} \bar{C}} x \\
 = & (\text{fold}_{T_{\rho[\bar{\gamma} := \bar{C}]}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}}))_{\bar{B}} x \\
 : & (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{A}][\bar{\gamma} := \bar{C}]) \bar{B}
 \end{aligned}$$

i.e., for each \bar{B} and \bar{C}

$$(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi := \bar{\beta} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu \phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Set}} \rho d \eta)_{\bar{B} \bar{C}}$$

is a morphism from $(\mu T_{\rho[\bar{\gamma} := \bar{C}]}^{\text{Set}}) \bar{B}$ to $\llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}]$.

To see that this family of morphisms is natural in \bar{B} and \bar{C} , we observe that the following diagram commutes for all $\bar{f} : \bar{B} \rightarrow \bar{B}'$ and $\bar{g} : \bar{C} \rightarrow \bar{C}'$:

$$\begin{array}{ccc}
 (\mu T_{\rho[\bar{\gamma} := \bar{C}]}^{\text{Set}}) \bar{B} & \xrightarrow{(\text{fold}_{T_{\rho[\bar{\gamma} := \bar{C}]}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}}))_{\bar{B}}} & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{C}][\bar{\beta} := \bar{B}] \\
 \downarrow (\mu \sigma_{id \rho[\bar{\gamma} := \bar{g}]}^{\text{Set}})_{\bar{B}} & & \downarrow \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\gamma} := \bar{g}][\bar{\beta} := id_{\bar{B}}]} \\
 (\mu T_{\rho[\bar{\gamma} := \bar{C}']}^{\text{Set}}) \bar{B} & \xrightarrow{(\text{fold}_{T_{\rho[\bar{\gamma} := \bar{C}']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}'}))_{\bar{B}}} & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{C}'][\bar{\beta} := \bar{B}] \\
 \downarrow (\mu T_{\rho[\bar{\gamma} := \bar{C}']}^{\text{Set}}) \bar{f} & & \downarrow \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\gamma} := id_{\bar{C}'}][\bar{\beta} := \bar{f}]} \\
 (\mu T_{\rho[\bar{\gamma} := \bar{C}']}^{\text{Set}}) \bar{B}' & \xrightarrow{(\text{fold}_{T_{\rho[\bar{\gamma} := \bar{C}']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}'}))_{\bar{B}'}} & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\gamma} := \bar{C}'][\bar{\beta} := \bar{B}']
 \end{array}$$

Indeed, naturality of $\text{fold}_{T_{\rho[\bar{\gamma} := \bar{C}']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}'})$ ensures that the bottom diagram commutes. To see that the top one commutes is considerably more delicate.

To see that the top diagram commutes we first observe that, given a natural transformation $\Theta : H \rightarrow K : [\text{Set}^k, \text{Set}] \rightarrow [\text{Set}^k, \text{Set}]$, the fixpoint natural transformation $\mu \Theta : \mu H \rightarrow$

$\mu K : \text{Set}^k \rightarrow \text{Set}$ is defined to be $\text{fold}_H(\Theta(\mu K) \circ \text{in}_K)$, i.e., the unique morphism making the following square commute:

$$\begin{array}{ccc} H(\mu H) & \xrightarrow{H(\mu \Theta)} & H(\mu K) \\ \text{in}_H \downarrow & & \downarrow \Theta(\mu K) \\ \mu H & \xrightarrow{\mu \Theta} & \mu K \end{array}$$

Taking $\Theta = \sigma_f^{\text{Set}} : T_\rho^{\text{Set}} \rightarrow T_{\rho'}^{\text{Set}}$ gives that the following diagram commutes for any morphism of set environments $f : \rho \rightarrow \rho'$:

$$\begin{array}{ccc} T_\rho^{\text{Set}}(\mu T_\rho^{\text{Set}}) & \xrightarrow{T_\rho^{\text{Set}}(\mu \sigma_f^{\text{Set}})} & T_\rho^{\text{Set}}(\mu T_{\rho'}^{\text{Set}}) \\ \text{in}_{T_\rho^{\text{Set}}} \downarrow & & \downarrow \sigma_f^{\text{Set}}(\mu T_{\rho'}^{\text{Set}}) \\ \mu T_\rho^{\text{Set}} & \xrightarrow{\mu \sigma_f^{\text{Set}}} & \mu T_{\rho'}^{\text{Set}} \end{array} \quad (19)$$

We next observe that the action of the functor

$$\lambda \bar{B}. \lambda \bar{C}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\phi := F][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}]$$

on the morphisms $\bar{f} : B \rightarrow B', \bar{g} : C \rightarrow C'$ is given by

$$\begin{aligned} & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash H[\phi := F][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} \text{id}_\rho[\bar{\beta} := \bar{f}][\bar{\gamma} := \bar{g}] \\ = & \llbracket \Gamma; \bar{\alpha}, \bar{\gamma} \vdash H[\phi := F] \rrbracket^{\text{Set}} \text{id}_\rho[\bar{\alpha} := \bar{f}][\bar{\gamma} := \bar{g}] \\ = & \llbracket \Gamma; \phi, \bar{\alpha}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} \text{id}_\rho[\bar{\alpha} := \bar{f}][\bar{\gamma} := \bar{g}][\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \text{id}_{\rho[\bar{\beta} := A]}[\bar{\gamma} := \bar{g}]] \\ = & \llbracket \Gamma; \phi, \bar{\alpha}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} (\text{id}_{\rho[\bar{\gamma} := C']}[\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']][\bar{\alpha} := \bar{f}] \\ & \circ \text{id}_{\rho[\bar{\alpha} := B]}[\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']][\bar{\gamma} := \bar{g}]] \\ & \circ \text{id}_{\rho[\bar{\alpha} := B][\bar{\gamma} := C]}[\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \text{id}_{\rho[\bar{\beta} := A]}[\bar{\gamma} := \bar{g}]] \\ = & \llbracket \Gamma; \phi, \bar{\alpha}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} \text{id}_{\rho[\bar{\gamma} := C']}[\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']][\bar{\alpha} := \bar{f}] \\ & \circ \llbracket \Gamma; \phi, \bar{\alpha}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} \text{id}_{\rho[\bar{\alpha} := B]}[\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']][\bar{\gamma} := \bar{g}] \\ & \circ \llbracket \Gamma; \phi, \bar{\alpha}, \bar{\gamma} \vdash H \rrbracket^{\text{Set}} \text{id}_{\rho[\bar{\alpha} := B][\bar{\gamma} := C]}[\phi := \lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \text{id}_{\rho[\bar{\beta} := A]}[\bar{\gamma} := \bar{g}]] \\ = & T_{\rho[\bar{\gamma} := C']}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']) \bar{f} \\ & \circ (\sigma_{\text{id}_{\rho[\bar{\gamma} := C']}}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']))_{\bar{B}} \\ & \circ (T_{\rho[\bar{\gamma} := C']}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \text{id}_{\rho[\bar{\beta} := A]}[\bar{\gamma} := \bar{g}]))_{\bar{B}} \end{aligned}$$

So, if η is a natural transformation from

$$\lambda \bar{B}. \lambda \bar{C}. \llbracket \Gamma; \bar{\alpha}, \bar{\gamma} \vdash H[\phi := F][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}]$$

to

$$\lambda \bar{B}. \lambda \bar{C}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}]$$

then, by naturality,

$$\begin{aligned}
 & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\beta} := f][\bar{\gamma} := g]} \circ \eta_{\bar{B}, \bar{C}} \\
 &= \eta_{\bar{B}', \bar{C}'} \circ \llbracket \Gamma; \bar{\alpha}, \bar{\gamma} \vdash H[\bar{\alpha} := F][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Set}} id_{\rho[\bar{\beta} := f][\bar{\gamma} := g]} \\
 &= \eta_{\bar{B}', \bar{C}'} \circ T_{\rho[\bar{\gamma} := C']}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']) \bar{f} \\
 &\quad \circ (\sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']))_{\bar{B}} \\
 &\quad \circ (T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\beta} := A][\bar{\gamma} := g]}))_{\bar{B}}
 \end{aligned}$$

As a special case when $\bar{f} = id_{\bar{B}}$ we have

$$\begin{aligned}
 & \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\beta} := B][\bar{\gamma} := g]} \circ \eta_{\bar{B}, \bar{C}} \\
 &= \eta_{\bar{B}, \bar{C}'} \circ (\sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']))_{\bar{B}} \\
 &\quad \circ (T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\beta} := A][\bar{\gamma} := g]}))_{\bar{B}}
 \end{aligned}$$

i.e.,

$$\begin{aligned}
 & \lambda \bar{B}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\beta} := B][\bar{\gamma} := g]} \circ \eta_{\bar{B}, \bar{C}} \\
 &= \lambda \bar{B}. \eta_{\bar{B}, \bar{C}'} \circ \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := A][\bar{\gamma} := C']) \quad (20) \\
 &\quad \circ T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\lambda \bar{A}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} id_{\rho[\bar{\beta} := A][\bar{\gamma} := g]})
 \end{aligned}$$

Now, to see that the top diagram in the diagram on page 46 commutes we first note that the diagram

$$\begin{array}{ccc}
 T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\mu T_{\rho[\bar{\gamma} := C]}^{\text{Set}}) & \xrightarrow{T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\text{fold}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ \mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}}))} & T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\lambda \bar{B}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := B][\bar{\gamma} := C']) \\
 \downarrow \text{in}_{T_{\rho[\bar{\gamma} := C]}^{\text{Set}}} & & \downarrow \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\lambda \bar{B}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := B][\bar{\gamma} := C']) \\
 & & T_{\rho[\bar{\gamma} := C']}^{\text{Set}} (\lambda \bar{B}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := B][\bar{\gamma} := C']) \\
 & & \downarrow \lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \\
 \mu T_{\rho[\bar{\gamma} := C]}^{\text{Set}} & \xrightarrow{\mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}}} \mu T_{\rho[\bar{\gamma} := C']}^{\text{Set}} \xrightarrow{\text{fold}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ \mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}})} & \lambda \bar{B}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := B][\bar{\gamma} := C']
 \end{array}$$

commutes because

$$\begin{aligned}
 & \lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\lambda \bar{B}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := B][\bar{\gamma} := C']) \\
 &\quad \circ T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\text{fold}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ \mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}})) \\
 &= \lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\lambda \bar{B}. \llbracket \Gamma; \bar{\beta}, \bar{\gamma} \vdash F \rrbracket^{\text{Set}} \rho[\bar{\beta} := B][\bar{\gamma} := C']) \\
 &\quad \circ T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\text{fold}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A}, \bar{C}'})) \circ T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}}) \\
 &= \lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\text{fold}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A}, \bar{C}'})) \circ \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\mu T_{\rho[\bar{\gamma} := C']}^{\text{Set}}) \circ T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}}) \\
 &= \text{fold}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ \text{in}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}}) \circ \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}} (\mu T_{\rho[\bar{\gamma} := C']}^{\text{Set}}) \circ T_{\rho[\bar{\gamma} := C]}^{\text{Set}} (\mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}}) \\
 &= \text{fold}_{T_{\rho[\bar{\gamma} := C']}^{\text{Set}}} (\lambda \bar{A}. \eta_{\bar{A}, \bar{C}'} \circ \mu \sigma_{id_{\rho[\bar{\gamma} := g]}}^{\text{Set}}) \circ \text{in}_{T_{\rho[\bar{\gamma} := C]}^{\text{Set}}}
 \end{aligned}$$

Here, the first equality is by functoriality of $T_{\rho[Y:=C]}^{\text{Set}}$, the second equality is by naturality of $\sigma_{id_{\rho[Y:=g]}}^{\text{Set}}$, the third equality by the universal property of $\text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}})$ and the last equality by Equation 19. That is, we have

$$\begin{aligned} & \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}}) \circ \mu\sigma_{id_{\rho[Y:=g]}}^{\text{Set}} \\ &= \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}} \circ \sigma_{id_{\rho[Y:=g]}}^{\text{Set}})(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}']) \end{aligned} \quad (21)$$

Next, we note that the diagram

$$\begin{array}{ccc} T_{\rho[Y:=C]}^{\text{Set}}(\mu T_{\rho[Y:=C]}^{\text{Set}}) & \xrightarrow{T_{\rho[Y:=C]}^{\text{Set}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} \circ \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}}))} & T_{\rho[Y:=C]}^{\text{Set}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}']) \\ \downarrow \text{in}_{T_{\rho[Y:=C]}^{\text{Set}}} & & \downarrow \sigma_{id_{\rho[\bar{\gamma}:=\bar{g}]}^{\text{Set}}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}']) \\ \mu T_{\rho[Y:=C]}^{\text{Set}} & \xrightarrow{\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}']} & \lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}'] \\ \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}}) & \xrightarrow{\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} } & \lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}'] \end{array}$$

commutes because

$$\begin{aligned} & \lambda\bar{A}.\eta_{\bar{A},\bar{C}} \circ \sigma_{id_{\rho[\bar{\gamma}:=\bar{g}]}^{\text{Set}}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}']) \\ & \quad \circ T_{\rho[Y:=C]}^{\text{Set}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} \circ \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}})) \\ &= \lambda\bar{A}.\eta_{\bar{A},\bar{C}} \circ \sigma_{id_{\rho[\bar{\gamma}:=\bar{g}]}^{\text{Set}}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}']) \\ & \quad \circ T_{\rho[Y:=C]}^{\text{Set}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} \circ \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}})) \\ &= \lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} \circ \lambda\bar{A}.\eta_{\bar{A},\bar{C}} \circ T_{\rho[Y:=C]}^{\text{Set}}(\text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}})) \\ &= \lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} \circ \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}}) \circ \text{in}_{T_{\rho[Y:=C]}^{\text{Set}}} \end{aligned}$$

Here, the first equality is by functoriality of $T_{\rho[Y:=C]}^{\text{Set}}$, the second equality is by Equation 20, and the last equality is by the universal property of $\text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}})$. That is, we have

$$\begin{aligned} & \lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} \circ \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}}) \\ &= \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}} \circ \sigma_{id_{\rho[\bar{\gamma}:=\bar{g}]}^{\text{Set}}}(\lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} \rho[\bar{\beta} := \bar{B}][\bar{\gamma} := \bar{C}'])) \end{aligned} \quad (22)$$

Combining Equations 21 and 22 we get that

$$\text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}}) \circ \mu\sigma_{id_{\rho[\bar{\gamma}:=\bar{g}]}^{\text{Set}}} = \lambda\bar{B}.\llbracket\Gamma;\bar{\beta},\bar{\gamma} \vdash F\rrbracket^{\text{Set}} id_{\rho[\bar{\beta}:=\bar{B}][\bar{\gamma}:=\bar{g}]} \circ \text{fold}_{T_{\rho[Y:=C]}^{\text{Set}}}(\lambda\bar{A}.\eta_{\bar{A},\bar{C}})$$

i.e., that the top diagram in the diagram on page 46 commutes. We therefore have that

$$(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Set}} \rho d \eta)_{\bar{B} \bar{C}}$$

is natural in \bar{B} and \bar{C} as desired.

– To see that, for every $\rho : \text{SetEnv}$, $d \in \llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Set}} \rho$, and $\eta : \llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F \rrbracket^{\text{Set}} \rho$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Set}} \rho d \eta$$

satisfies the additional condition necessary for it to be in $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F \rrbracket^{\text{Set}} \rho$, let $\bar{R} : \text{Rel}(\bar{B}, \bar{B}')$ and $\bar{S} : \text{Rel}(\bar{C}, \bar{C}')$. Since η satisfies the additional condition necessary for it to be in $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} (H[\phi := F][\bar{\alpha} := \bar{\beta}]) F \rrbracket^{\text{Set}} \rho$ – i.e., since

$$\begin{aligned} (\eta_{\bar{B} \bar{C}}, \eta_{\bar{B}' \bar{C}'}) &\in \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash H[\phi := F][\bar{\alpha} := \bar{\beta}] \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}] \rightarrow \\ &\quad \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}] \\ &= T_{\text{Eq}_\rho[\bar{\gamma} := \bar{S}]} (\llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}]) \rightarrow \\ &\quad \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}] \end{aligned}$$

– we have that

$$((\text{fold}_{T_{\text{Set}} \rho[\bar{\gamma} := \bar{C}]} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}}))_{\bar{B}}, (\text{fold}_{T_{\text{Set}} \rho[\bar{\gamma} := \bar{C}']} (\lambda \bar{A}. \eta_{\bar{A} \bar{C}'}))_{\bar{B}'})$$

has type

$$\begin{aligned} &(\mu T_{\text{Eq}_\rho[\bar{\gamma} := \bar{S}]} \bar{R}) \rightarrow \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}] \\ &= (\mu T_{\text{Eq}_\rho[\bar{\gamma} := \bar{S}]} \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash \beta \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}]) \rightarrow \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}] \\ &= \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}] \rightarrow \llbracket \Gamma; \bar{\gamma}, \bar{\beta} \vdash F \rrbracket^{\text{Rel}} \text{Eq}_\rho[\bar{\gamma} := \bar{S}][\bar{\beta} := \bar{R}] \end{aligned}$$

as desired.

– The proofs that

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Rel}} \rho$$

is a natural transformation from $\llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Rel}}$ to

$$\llbracket \Gamma; \emptyset \vdash \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Rel}}$$

and that, for all $\rho : \text{RelEnv}$ and the unique $d : \llbracket \Gamma; \emptyset \vdash \emptyset \rrbracket^{\text{Rel}} \rho$,

$$\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Rel}} \rho d$$

is a morphism from $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F \rrbracket^{\text{Rel}} \rho$ to $\llbracket \Gamma; \emptyset \vdash \text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F \rrbracket^{\text{Rel}} \rho$, are analogous.

– Finally, to see that

$$\begin{aligned} &\pi_i(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Rel}} \rho) \\ &= \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^0 (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Set}} (\pi_i \rho) \end{aligned}$$

we compute

$$\begin{aligned}
& \pi_i(\llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^\emptyset (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Rel}}) \\
&= \pi_i(\lambda e \eta \bar{R} \bar{S}. (\text{fold}_{T_{\rho[\bar{Y} := \bar{S}]}} (\lambda \bar{Z}. \eta \bar{Z} \bar{S}))_{\bar{R}}) \\
&= \lambda e \eta \bar{R} \bar{S}. (\text{fold}_{T_{(\pi_i \rho)[\bar{Y} := \pi_i \bar{S}]}} (\lambda \bar{Z}. (\pi_i \eta)_{\pi_i \bar{Z} \pi_i \bar{S}}))_{\pi_i \bar{R}} \\
&= \lambda d \eta \bar{B} \bar{C}. (\text{fold}_{T_{(\pi_i \rho)[\bar{Y} := \bar{C}]}} (\lambda \bar{A}. \eta \bar{A} \bar{C}))_{\bar{B}} \\
&= \llbracket \Gamma; \emptyset \mid \emptyset \vdash \text{fold}_H^F : \text{Nat}^\emptyset (\text{Nat}^{\bar{\beta}, \bar{\gamma}} H[\phi :=_{\bar{\beta}} F][\bar{\alpha} := \bar{\beta}] F) (\text{Nat}^{\bar{\beta}, \bar{\gamma}} (\mu\phi. \lambda \bar{\alpha}. H) \bar{\beta} F) \rrbracket^{\text{Rel}}(\pi_i \rho)
\end{aligned}$$

Here, we are again using the fact that π_1 and π_2 are surjective.

□

The Abstraction Theorem is now the special case of Theorem 36 for closed terms of close type:

State more generally as: If $(a, b) \in \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rho$ then $(\llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_1 \rho)a, \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}}(\pi_2 \rho)b) \in \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Set}} \rho$. Get the next theorem as a corollary for closed terms of closed type.

THEOREM 37. *If $\vdash \tau : \mathcal{F}$ and $\vdash t : \tau$, then $(\llbracket \vdash t : \tau \rrbracket^{\text{Set}}, \llbracket \vdash t : \tau \rrbracket^{\text{Set}}) \in \llbracket \vdash \tau \rrbracket^{\text{Rel}}$.*

Our calculus does not support Church encodings of data types like pair or sum or list types because all of the “forall”s in our calculus must be at the top level. Nevertheless, our calculus does admit actual sum and product and list types because they are coded by μ -terms in our calculus. We just don’t have an equivalence of these types and their Church encodings in our calculus, that’s all.

6 FREE THEOREMS FOR NESTED TYPES

6.1 Free Theorem for Type of Polymorphic Bottom

Suppose $\vdash g : \text{Nat}^\alpha \perp \alpha$, let $G^{\text{Set}} = \llbracket \vdash g : \text{Nat}^\alpha \perp \alpha \rrbracket^{\text{Set}}$, and let $G^{\text{Rel}} = \llbracket \vdash g : \text{Nat}^\alpha \perp \alpha \rrbracket^{\text{Rel}}$. By Theorem 37, $(G^{\text{Set}}(\pi_1 \rho), G^{\text{Set}}(\pi_2 \rho)) = G^{\text{Rel}} \rho$. Thus, for all $\rho \in \text{RelEnv}$ and any $(a, b) \in \llbracket \vdash \emptyset \rrbracket^{\text{Rel}} \rho = 1$, eliding the only possible instantiations of a and b gives that

$$\begin{aligned}
(G^{\text{Set}}, G^{\text{Set}}) &= (G^{\text{Set}}(\pi_1 \rho), G^{\text{Set}}(\pi_2 \rho)) \in \llbracket \vdash \text{Nat}^\alpha \perp \alpha \rrbracket^{\text{Rel}} \rho \\
&= \{\eta : K_1 \Rightarrow id\} \\
&= \{(\eta_1 : K_1 \Rightarrow id, \eta_2 : K_1 \Rightarrow id)\}
\end{aligned}$$

That is, G^{Set} is a natural transformation from the constantly 1-valued functor to the identity functor in Set. In particular, for every $S : \text{Set}$, $G_S^{\text{Set}} : 1 \rightarrow S$. Note, however, that if $S = \emptyset$, then there can be no such morphism, so no such natural transformation can exist in Set, and thus no term $\vdash g : \text{Nat}^\alpha \perp \alpha$ can exist in our calculus. That is, our calculus does not admit any terms with the closed type $\text{Nat}^\alpha \perp \alpha$ of the polymorphic bottom.

6.2 Free Theorem for Type of Polymorphic Identity

Suppose $\vdash g : \text{Nat}^\alpha \alpha \alpha$, let $G^{\text{Set}} = \llbracket \vdash g : \text{Nat}^\alpha \alpha \alpha \rrbracket^{\text{Set}}$, and let $G^{\text{Rel}} = \llbracket \vdash g : \text{Nat}^\alpha \alpha \alpha \rrbracket^{\text{Rel}}$. By Theorem 37, $(G^{\text{Set}}(\pi_1 \rho), G^{\text{Set}}(\pi_2 \rho)) = G^{\text{Rel}} \rho$. Thus, for all $\rho \in \text{RelEnv}$ and any $(a, b) \in \llbracket \vdash \emptyset \rrbracket^{\text{Rel}} \rho = 1$, eliding the only possible instantiations of a and b gives that

$$\begin{aligned}
(G^{\text{Set}}, G^{\text{Set}}) &= (G^{\text{Set}}(\pi_1 \rho), G^{\text{Set}}(\pi_2 \rho)) \in \llbracket \vdash \text{Nat}^\alpha \alpha \alpha \rrbracket^{\text{Rel}} \rho \\
&= \{\eta : id \Rightarrow id\} \\
&= \{(\eta_1 : id \Rightarrow id, \eta_2 : id \Rightarrow id)\}
\end{aligned}$$

That is, G^{Set} is a natural transformation from the identity functor on Set to itself.

Now let S be any set. If $S = \emptyset$, then there is exactly one morphism $id_S : S \rightarrow S$, so $G_S^{\text{Set}} : S \rightarrow S$ must be id_S . If $S \neq \emptyset$, then if a is any element of S and $K_a : S \rightarrow S$ is the constantly a -valued morphism on S , then instantiating the naturality square implied by the above equality gives that

$G_S^{\text{Set}} \circ K_a = K_a \circ G_S^{\text{Set}}$, i.e., $G_S^{\text{Set}} a = a$, i.e., $G_S^{\text{Set}} = id_S$. Putting these two cases together we have that for every $S : \text{Set}$, $G_S^{\text{Set}} = id_S$, i.e., G^{Set} is the identity natural transformation for the identity functor on Set . So every closed term g of closed type $\text{Nat}^\alpha \alpha$ always denotes the identity natural transformation for the identity functor on Set , i.e., every closed term g of type $\text{Nat}^\alpha \alpha$ denotes the polymorphic identity function.

6.3 Free Theorem for Type of filter for Lists

Let $\text{List } \alpha = (\mu\phi.\lambda\beta.\mathbb{1} + \beta \times \phi\beta)\alpha$, and let $\text{map} = \text{map}_{\lambda A. \llbracket \emptyset; \alpha \vdash \text{List } \alpha \rrbracket^{\text{Set}} \rho[\alpha := A]}$.

LEMMA 38. *If $g : A \rightarrow B$, $\rho : \text{RelEnv}$, and $\rho\alpha = (A, B, \langle g \rangle)$, then $\llbracket \alpha; \emptyset \vdash \text{List } \alpha \rrbracket^{\text{Rel}} \rho = \langle \text{map } g \rangle$*

PROOF.

$$\begin{aligned}
 & \llbracket \alpha; \emptyset \vdash \text{List } \alpha \rrbracket^{\text{Rel}} \rho \\
 &= \mu T_\rho (\llbracket \alpha; \emptyset \vdash \alpha \rrbracket^{\text{Rel}} \rho) \\
 &= \mu T_\rho (A, B, \langle g \rangle) \\
 &= (\mu T_{\pi_1 \rho} A, \mu T_{\pi_2 \rho} B, \lim_{n \in \mathbb{N}} (T_\rho^n K_0)^* (A, B, \langle g \rangle)) \\
 &= (\text{List } A, \text{List } B, \lim_{n \in \mathbb{N}} \sum_{i=0}^n (A, B, \langle g \rangle)^i) \\
 &= (\text{List } A, \text{List } B, \text{List } (A, B, \langle g \rangle)) \\
 &= (\text{List } A, \text{List } B, \langle \text{map } g \rangle)
 \end{aligned}$$

The first equality is by Definition 21, the third equality is by Equation 3, and the fourth and sixth equalities are by Equations 23 and 24 below.

The following sequence of equalities shows

$$(T_\rho^n K_0)^* R = \sum_{i=0}^n R^i \quad (23)$$

by induction on n :

$$\begin{aligned}
 & (T_\rho^n K_0)^* R \\
 &= T_\rho^{\text{Rel}} (T_\rho^{n-1} K_0)^* R \\
 &= \llbracket \alpha; \phi, \beta \vdash \mathbb{1} + \beta \times \phi\beta \rrbracket^{\text{Set}} \rho[\phi := (T_\rho^{n-1} K_0)^*][\beta := R] \\
 &= \mathbb{1} + R \times (T_\rho^{n-1} K_0)^* R \\
 &= \mathbb{1} + R \times (\sum_{i=0}^{n-1} R^i) \\
 &= \sum_{i=0}^n R^i
 \end{aligned}$$

The following reasoning shows

$$\text{List } (A, B, \langle g \rangle) = \langle \text{map } g \rangle \quad (24)$$

By showing that $(xs, xs') \in \text{List } (A, B, \langle g \rangle)$ if and only if $(xs, xs') \in \langle \text{map } g \rangle$:

$$\begin{aligned}
 & (xs, xs') \in \text{List } (A, B, \langle g \rangle) \\
 & \iff \forall i. (xs_i, xs'_i) \in \langle g \rangle \\
 & \iff \forall i. xs'_i = g(xs_i) \\
 & \iff xs' = \text{map } g \ xs \\
 & \iff (xs, xs') \in \langle \text{map } g \rangle
 \end{aligned}$$

□

THEOREM 39. If $\Gamma; \Phi \mid \Delta \vdash t : \tau$ and $\rho \in \text{RelEnv}$, and if $(a, b) \in \llbracket \Gamma; \Phi \vdash \Delta \rrbracket^{\text{Rel}} \rho$, then
 $(\llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}}(\pi_1 \rho) a, \llbracket \Gamma; \Phi \mid \Delta \vdash t : \tau \rrbracket^{\text{Set}}(\pi_2 \rho) b) \in \llbracket \Gamma; \Phi \vdash \tau \rrbracket^{\text{Rel}} \rho$

PROOF. Immediate from Theorem 36 (at-gen). \square

THEOREM 40. If $g : A \rightarrow B$, $\rho : \text{RelEnv}$, $\rho\alpha = (A, B, \langle g \rangle)$, $(a, b) \in \llbracket \alpha; \emptyset \vdash \Delta \rrbracket^{\text{Rel}} \rho$, $(s \circ g, s) \in \llbracket \alpha; \emptyset \vdash \text{Nat}^0 \alpha \text{Bool} \rrbracket^{\text{Rel}} \rho$, and, for some well-formed term filter,

$$t = \llbracket \alpha; \emptyset \mid \Delta \vdash \text{filter} : \text{Nat}^0 (\text{Nat}^0 \alpha \text{Bool}) (\text{Nat}^0 (\text{List } \alpha) (\text{List } \alpha)) \rrbracket^{\text{Set}}, \text{ then}$$

$$\text{map } g \circ t(\pi_1 \rho) a (s \circ g) = t(\pi_2 \rho) b s \circ \text{map } g$$

PROOF. By Theorem 39, $(t(\pi_1 \rho) a, t(\pi_2 \rho) b) \in \llbracket \alpha; \emptyset \vdash \text{Nat}^0 (\text{Nat}^0 \alpha \text{Bool}) (\text{Nat}^0 (\text{List } \alpha) (\text{List } \alpha)) \rrbracket^{\text{Rel}} \rho$. Thus if $(s, s') \in \llbracket \alpha; \emptyset \vdash \text{Nat}^0 \alpha \text{Bool} \rrbracket^{\text{Rel}} \rho = \rho\alpha \rightarrow \text{Eq}_{\text{Bool}}$, then

$$\begin{aligned} (t(\pi_1 \rho) a s, t(\pi_2 \rho) b s') &\in \llbracket \alpha; \emptyset \vdash \text{Nat}^0 (\text{List } \alpha) (\text{List } \alpha) \rrbracket^{\text{Rel}} \rho \\ &= \llbracket \alpha; \emptyset \vdash \text{List } \alpha \rrbracket^{\text{Rel}} \rho \rightarrow \llbracket \alpha; \emptyset \vdash \text{List } \alpha \rrbracket^{\text{Rel}} \rho \end{aligned}$$

So if $(xs, xs') \in \llbracket \alpha; \emptyset \vdash \text{List } \alpha \rrbracket^{\text{Rel}} \rho$ then,

$$(t(\pi_1 \rho) a s xs, t(\pi_2 \rho) b s' xs') \in \llbracket \alpha; \emptyset \vdash \text{List } \alpha \rrbracket^{\text{Rel}} \rho \quad (25)$$

Consider the case in which $\rho\alpha = (A, B, \langle g \rangle)$. Then $\llbracket \alpha; \emptyset \vdash \text{List } \alpha \rrbracket^{\text{Rel}} \rho = \langle \text{map } g \rangle$, by Lemma 38, and $(xs, xs') \in \langle \text{map } g \rangle$ implies $xs' = \text{map } g xs$. We also have that $(s, s') \in \langle g \rangle \rightarrow \text{Eq}_{\text{Bool}}$ implies $\forall (x, gx) \in \langle g \rangle. sx = s'(gx)$ and thus $s = s' \circ g$ due to the definition of morphisms between relations. With these instantiations, Equation 26 becomes

$$\begin{aligned} (t(\pi_1 \rho) a (s' \circ g) xs, t(\pi_2 \rho) b s' (\text{map } g xs)) &\in \langle \text{map } g \rangle, \\ \text{i.e.,} \\ \text{map } g (t(\pi_1 \rho) a (s' \circ g) xs) &= t(\pi_2 \rho) b s' (\text{map } g xs), \\ \text{i.e.,} \\ \text{map } g \circ t(\pi_1 \rho) a (s' \circ g) &= t(\pi_2 \rho) b s' \circ \text{map } g \end{aligned}$$

as desired. \square

6.4 Free Theorem for Type of filter for GROSE

THEOREM 41. Let $g : A \rightarrow B$ be a function, $\eta : F \rightarrow G$ a natural transformation of Set functors, $\rho : \text{RelEnv}$, $\rho\alpha = (A, B, \langle g \rangle)$, $\rho\psi = (F, G, \langle \eta \rangle)$, $(a, b) \in \llbracket \alpha; \psi; \emptyset \vdash \Delta \rrbracket^{\text{Rel}} \rho$, and $(s \circ g, s) \in \llbracket \alpha; \emptyset \vdash \text{Nat}^0 \alpha \text{Bool} \rrbracket^{\text{Rel}} \rho$. Then, for any well-formed term filter, if we call

$$t = \llbracket \alpha; \psi; \emptyset \mid \Delta \vdash \text{filter} : \text{Nat}^0 (\text{Nat}^0 \alpha \text{Bool}) (\text{Nat}^0 (\text{List } \alpha) (\text{List } \alpha)) \rrbracket^{\text{Set}}$$

we have that

$$\text{map } \eta (g + 1) \circ t(\pi_1 \rho) a (s \circ g) = t(\pi_2 \rho) b s \circ \text{map } \eta g$$

PROOF. By Theorem 39,

$$(t(\pi_1 \rho) a, t(\pi_2 \rho) b) \in \llbracket \alpha; \psi; \emptyset \vdash \text{Nat}^0 (\text{Nat}^0 \alpha \text{Bool}) (\text{Nat}^0 (\text{List } \alpha) (\text{List } \alpha)) \rrbracket^{\text{Rel}} \rho$$

Thus if $(s, s') \in \llbracket \alpha; \emptyset \vdash \text{Nat}^0 \alpha \text{ Bool} \rrbracket^{\text{Rel}} \rho = \rho \alpha \rightarrow \text{Eq}_{\text{Bool}}$, then

$$\begin{aligned} (t(\pi_1 \rho) a s, t(\pi_2 \rho) b s') &\in \llbracket \alpha, \psi; \emptyset \vdash \text{Nat}^0 (\text{GRose } \psi \alpha) (\text{GRose } \psi (\alpha + \mathbb{1})) \rrbracket^{\text{Rel}} \rho \\ &= \llbracket \alpha, \psi; \emptyset \vdash \text{GRose } \psi \alpha \rrbracket^{\text{Rel}} \rho \rightarrow \llbracket \alpha, \psi; \emptyset \vdash \text{GRose } \psi (\alpha + \mathbb{1}) \rrbracket^{\text{Rel}} \rho \end{aligned}$$

So if $(xs, xs') \in \llbracket \alpha; \emptyset \vdash \text{GRose } \psi \alpha \rrbracket^{\text{Rel}} \rho$ then,

$$(t(\pi_1 \rho) a s xs, t(\pi_2 \rho) b s' xs') \in \llbracket \alpha, \psi; \emptyset \vdash \text{GRose } \psi (\alpha + \mathbb{1}) \rrbracket^{\text{Rel}} \rho \quad (26)$$

Since $\rho \alpha = (A, B, \langle g \rangle)$ and $\rho \psi = (F, G, \langle \psi \rangle)$, then $\llbracket \alpha, \psi; \emptyset \vdash \text{GRose } \psi \alpha \rrbracket^{\text{Rel}} \rho = \langle \text{map } \eta g \rangle$ and $\llbracket \alpha, \psi; \emptyset \vdash \text{GRose } \psi (\alpha + \mathbb{1}) \rrbracket^{\text{Rel}} \rho = \langle \text{map } \eta (g + 1) \rangle$, by Lemma 38. Moreover, $(xs, xs') \in \langle \text{map } \eta g \rangle$ implies $xs' = \text{map } \eta g xs$. We also have that $(s, s') \in \langle g \rangle \rightarrow \text{Eq}_{\text{Bool}}$ implies $\forall (x, gx) \in \langle g \rangle. sx = s'(gx)$ and thus $s = s' \circ g$ due to the definition of morphisms between relations. With these instantiations, Equation 26 becomes

$$\begin{aligned} (t(\pi_1 \rho) a (s' \circ g) xs, t(\pi_2 \rho) b s' (\text{map } \eta g xs)) &\in \langle \text{map } \eta (g + 1) \rangle, \\ \text{i.e.,} \\ \text{map } \eta (g + 1) (t(\pi_1 \rho) a (s' \circ g) xs) &= t(\pi_2 \rho) b s' (\text{map } \eta g xs), \\ \text{i.e.,} \\ \text{map } \eta (g + 1) \circ t(\pi_1 \rho) a (s' \circ g) &= t(\pi_2 \rho) b s' \circ \text{map } \eta g \end{aligned}$$

as desired. □

6.5 Short Cut Fusion for Lists

THEOREM 42. Let $\vdash \tau : \mathcal{F}, \vdash \tau' : \mathcal{F}$, and $\beta; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^0(\mathbb{1} + \tau \times \beta) \beta) \beta$. If

$$G = \llbracket \beta; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^0(\mathbb{1} + \tau \times \beta) \beta) \beta \rrbracket^{\text{Set}}$$

then

$$\text{fold}_{1+\tau \times _} n c (G (\text{List } \llbracket \vdash \tau \rrbracket^{\text{Set}}) \text{nil cons}) = G \llbracket \vdash \tau' \rrbracket^{\text{Set}} n c$$

PROOF. Let $\vdash \tau : \mathcal{F}$ and $\vdash \tau' : \mathcal{F}$, let

$$\beta; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^0(\mathbb{1} + \tau \times \beta) \beta) \beta$$

and let

$$G = \llbracket \beta; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^0(\mathbb{1} + \tau \times \beta) \beta) \beta \rrbracket^{\text{Set}}$$

Then Theorem 37 gives that, for any relation environment ρ and any $(a, b) \in \llbracket \beta; \emptyset \mid \emptyset \rrbracket^{\text{Rel}} \rho = 1$, then (eliding the only possible instantiations of a and b) we have

$$(G (\pi_1 \rho), G (\pi_2 \rho)) \in \llbracket \beta; \emptyset \vdash \text{Nat}^0(\text{Nat}^0(\mathbb{1} + \tau \times \beta) \beta) \beta \rrbracket^{\text{Rel}} \rho$$

Since

$$\begin{aligned} &\llbracket \beta; \emptyset \vdash \text{Nat}^0(\text{Nat}^0(\mathbb{1} + \tau \times \beta) \beta) \beta \rrbracket^{\text{Rel}} \rho \\ &= \llbracket \beta; \emptyset \vdash \text{Nat}^0(\mathbb{1} + \tau \times \beta) \beta \rrbracket^{\text{Rel}} \rho \rightarrow \rho \beta \\ &= (\llbracket \beta; \emptyset \vdash \mathbb{1} + \tau \times \beta \rrbracket^{\text{Rel}} \rho \rightarrow \rho \beta) \rightarrow \rho \beta \\ &= ((\mathbb{1} + \llbracket \vdash \tau \rrbracket^{\text{Rel}} \rho \times \rho \beta) \rightarrow \rho \beta) \rightarrow \rho \beta \\ &\cong (((\llbracket \vdash \tau \rrbracket^{\text{Rel}} \rho \times \rho \beta) \rightarrow \rho \beta) \times \rho \beta) \rightarrow \rho \beta \end{aligned}$$

we have that if $(c', c) \in \llbracket \vdash \tau \rrbracket^{\text{Rel}} \rho \times \rho \beta \rightarrow \rho \beta$ and $(n', n) \in \rho \beta$, then

$$(G (\pi_1 \rho) n' c', G (\pi_2 \rho) n c) \in \rho \beta$$

Now note that

$$\llbracket \vdash \text{fold}_{\mathbb{1}+\tau \times \beta}^{\tau'} : \text{Nat}^0(\text{Nat}^0(\mathbb{1} + \tau \times \tau') \tau') (\text{Nat}^0(\mu\alpha. \mathbb{1} + \tau \times \alpha) \tau') \rrbracket^{\text{Set}} = \text{fold}_{\mathbb{1}+\tau \times _}$$

and observe that if $c \in \llbracket \vdash \tau \rrbracket^{\text{Set}} \times \llbracket \vdash \tau' \rrbracket^{\text{Set}} \rightarrow \llbracket \vdash \tau' \rrbracket^{\text{Set}}$ and $n \in \llbracket \vdash \tau' \rrbracket^{\text{Set}}$, then

$$(n, c) \in \llbracket \vdash \text{Nat}^0(\mathbb{1} + \tau \times \tau') \tau' \rrbracket^{\text{Set}}$$

Consider the instantiation:

$$\begin{aligned} \pi_1 \rho \beta &= \llbracket \vdash \mu\alpha. \mathbb{1} + \tau \times \alpha \rrbracket^{\text{Set}} = \text{List } \llbracket \vdash \tau \rrbracket^{\text{Set}} \\ \pi_2 \rho \beta &= \llbracket \vdash \tau' \rrbracket^{\text{Set}} \\ \rho \beta &= \langle \text{fold}_{\mathbb{1}+\tau \times _} n c \rangle : \text{Rel}(\pi_1 \rho \beta, \pi_2 \rho \beta) \\ c' &= \text{cons} \\ n' &= \text{nil} \end{aligned}$$

Clearly, $(\text{nil}, n) \in \rho \beta = \langle \text{fold}_{\mathbb{1}+\tau \times _} n c \rangle$ because $\text{fold}_{\mathbb{1}+\tau \times _} n c \text{ nil} = n$. Moreover, $(\text{cons}, c) \in \llbracket \vdash \tau \rrbracket^{\text{Rel}} \times \rho \beta \rightarrow \rho \beta$ since if $(x, x') \in \llbracket \vdash \tau \rrbracket^{\text{Rel}}$, i.e., $x = x'$, and if $(y, y') \in \rho \beta = \langle \text{fold}_{\mathbb{1}+\tau \times _} n c \rangle$, i.e., $y' = \text{fold}_{\mathbb{1}+\tau \times _} n c y$, then

$$(\text{cons } x y, c x (\text{fold}_{\mathbb{1}+\tau \times _} n c y)) \in \langle \text{fold}_{\mathbb{1}+\tau \times _} n c \rangle$$

i.e.,

$$c x (\text{fold}_{\mathbb{1}+\tau \times _} n c y) = \text{fold}_{\mathbb{1}+\tau \times _} n c (\text{cons } x y)$$

holds by definition of $\text{fold}_{\mathbb{1}+\tau \times _}$. We therefore conclude that

$$(G (\text{List } \llbracket \vdash \tau \rrbracket^{\text{Set}}) \text{ nil cons}, G \llbracket \vdash \tau' \rrbracket^{\text{Set}} n c) \in \langle \text{fold}_{\mathbb{1}+\tau \times _} n c \rangle$$

i.e., that

$$\text{fold}_{\mathbb{1}+\tau \times _} n c (G (\text{List } \llbracket \vdash \tau \rrbracket^{\text{Set}}) \text{ nil cons}) = G \llbracket \vdash \tau' \rrbracket^{\text{Set}} n c$$

□

6.6 Short Cut Fusion for Arbitrary ADTs

THEOREM 43. *Let $\vdash \tau : \mathcal{F}$, let $\vdash \tau' : \mathcal{F}$, let $\bar{\alpha}; \beta \vdash F : \mathcal{F}$, and let $\beta; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^0 F[\bar{\alpha} := \bar{\tau}] \beta) \beta$. If we regard*

$$\begin{aligned} H &= \llbracket \emptyset; \beta \vdash F[\bar{\alpha} := \bar{\tau}] \rrbracket^{\text{Set}} \\ G &= \llbracket \beta; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^0 F[\bar{\alpha} := \bar{\tau}] \beta) \beta \rrbracket^{\text{Set}} \end{aligned}$$

as functors in β , then for every $B \in H \llbracket \vdash \tau' \rrbracket^{\text{Set}} \rightarrow \llbracket \vdash \tau' \rrbracket^{\text{Set}}$ we have

$$\text{fold}_H B (G \mu H \text{ in}_H) = G \llbracket \vdash \tau' \rrbracket^{\text{Set}} B$$

PROOF. We first note that the type of g is well-formed, since $\emptyset; \beta \vdash F[\bar{\alpha} := \bar{\tau}] : \mathcal{F}$ so our promotion theorem gives that $\beta; \emptyset \vdash F[\bar{\alpha} := \bar{\tau}] : \mathcal{F}$, and $\emptyset; \beta \vdash \beta : \mathcal{F}$ so that our promotion theorem gives $\beta; \emptyset \vdash \beta : \mathcal{F}$. From these facts we deduce that $\beta; \emptyset \vdash \text{Nat}^0 F[\bar{\alpha} := \bar{\tau}] \beta : \mathcal{T}$, and thus that $\beta; \emptyset \vdash \text{Nat}^0(\text{Nat}^0 F[\bar{\alpha} := \bar{\tau}] \beta) \beta : \mathcal{T}$.

Theorem 37 gives that, for any relation environment ρ and any $(a, b) \in \llbracket \beta; \emptyset \vdash \emptyset \rrbracket^{\text{Rel}} \rho = 1$, eliding the only possible instantiations of a and b gives that

$$(G (\pi_1 \rho), G (\pi_2 \rho)) \in \llbracket \beta; \emptyset \vdash \text{Nat}^0(\text{Nat}^0 F[\bar{\alpha} := \bar{\tau}] \beta) \beta \rrbracket^{\text{Rel}} \rho$$

Since

$$\begin{aligned} &\llbracket \beta; \emptyset \vdash \text{Nat}^0(\text{Nat}^0 F[\bar{\alpha} := \bar{\tau}] \beta) \beta \rrbracket^{\text{Rel}} \rho \\ &= \llbracket \beta; \emptyset \vdash \text{Nat}^0 F[\bar{\alpha} := \bar{\tau}] \beta \rrbracket^{\text{Rel}} \rho \rightarrow \rho \beta \end{aligned}$$

we have that if $(A, B) \in \llbracket \beta; \emptyset \vdash \text{Nat}^0 F[\overline{\alpha := \tau}] \beta \rrbracket^{\text{Rel}} \rho$ then

$$(G(\pi_1 \rho) A, G(\pi_2 \rho) B) \in \rho \beta$$

Now note that

$$\llbracket \vdash \text{fold}_{F[\overline{\alpha := \tau}]}^{\tau'} : \text{Nat}^0 (\text{Nat}^0 F[\overline{\alpha := \tau}] [\beta := \tau'] \tau') (\text{Nat}^0 (\mu \beta. F[\overline{\alpha := \tau}] \tau'))^{\text{Set}} = \text{fold}_H$$

and consider the instantiation

$$\begin{aligned} A &= in_H : H(\mu H) \rightarrow \mu H \\ B &: H[\vdash \tau']^{\text{Set}} \rightarrow \llbracket \vdash \tau' \rrbracket^{\text{Set}} \\ \rho \beta &= \langle \text{fold}_H B \rangle \end{aligned}$$

(Note that all the types here are well-formed.) This gives

$$\begin{aligned} \pi_1 \rho \beta &= \llbracket \vdash \mu \beta. F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}} = \mu H \\ \pi_2 \rho \beta &= \llbracket \vdash \tau' \rrbracket^{\text{Set}} \\ \rho \beta &: \text{Rel}(\pi_1 \rho \beta, \pi_2 \rho \beta) \\ A &: \llbracket \beta; \emptyset \vdash \text{Nat}^0 F[\overline{\alpha := \tau}] \beta \rrbracket^{\text{Set}}(\pi_1 \rho) \\ B &: \llbracket \beta; \emptyset \vdash \text{Nat}^0 F[\overline{\alpha := \tau}] \beta \rrbracket^{\text{Set}}(\pi_2 \rho) \end{aligned}$$

since

$$\begin{aligned} A = in_H &: H(\mu H) \rightarrow \mu H \\ &= \llbracket \emptyset; \beta \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}}(\mu \llbracket \emptyset; \beta \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}}) \rightarrow \mu \llbracket \emptyset; \beta \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}} \\ &= \llbracket \emptyset; \beta \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}}(\pi_1 \rho) \rightarrow \llbracket \emptyset; \beta \vdash \beta \rrbracket^{\text{Set}}(\pi_1 \rho) \\ &= \llbracket \beta; \emptyset \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}}(\pi_1 \rho) \rightarrow \llbracket \beta; \emptyset \vdash \beta \rrbracket^{\text{Set}}(\pi_1 \rho) \quad \text{Daniel's trick; now a theorem} \\ &= \llbracket \beta; \emptyset \vdash \text{Nat}^0 F[\overline{\alpha := \tau}] \beta \rrbracket^{\text{Set}}(\pi_1 \rho) \end{aligned}$$

where “Daniel’s trick” is the observation that a functor can be seen as non-functorial when we only care about its action on objects. This is now a theorem. We also have

$$\begin{aligned} (A, B) = (in_H, B) &\in \llbracket \beta; \emptyset \vdash \text{Nat}^0 F[\overline{\alpha := \tau}] \beta \rrbracket^{\text{Rel}} \rho \\ &= \llbracket \beta; \emptyset \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Rel}} \rho [\beta := \langle \text{fold}_H B \rangle] \rightarrow \langle \text{fold}_H B \rangle \\ &= \llbracket \beta; \emptyset \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Rel}} \langle \text{fold}_H B \rangle \rightarrow \langle \text{fold}_H B \rangle \\ &= \llbracket \emptyset; \beta \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Rel}} \langle \text{fold}_H B \rangle \rightarrow \langle \text{fold}_H B \rangle \quad \text{Daniel's trick; now a theorem} \\ &= \langle \llbracket \emptyset; \beta \vdash F[\overline{\alpha := \tau}] \rrbracket^{\text{Set}} \langle \text{fold}_H B \rangle \rangle \rightarrow \langle \text{fold}_H B \rangle \quad \text{by the graph lemma} \\ &= \langle \text{map}_H \langle \text{fold}_H B \rangle \rangle \rightarrow \langle \text{fold}_H B \rangle \end{aligned}$$

since if $(x, y) \in \langle \text{map}_H \langle \text{fold}_H B \rangle \rangle$, i.e., if $\text{map}_H \langle \text{fold}_H B \rangle x = y$, then $\text{fold}_H B (in_H x) = B y = B (\text{map}_H \langle \text{fold}_H B \rangle x)$ by the definition of $\text{fold}_H B$ as a (indeed, the unique) morphism from in_H to B . Thus,

$$(G(\pi_1 \rho) A, G(\pi_2 \rho) B) \in \langle \text{fold}_H B \rangle$$

i.e.,

$$\text{fold}_H B (G(\pi_1 \rho) in_H) = G(\pi_2 \rho) B$$

Since β is the only free variable in G , this simplifies to

$$\text{fold}_H B (G \mu H in_H) = G \llbracket \vdash \tau' \rrbracket^{\text{Set}} B$$

□

6.7 Short Cut Fusion for Arbitrary Nested Types

Can take $\emptyset; \alpha \vdash c$ with $\llbracket \emptyset; \alpha \vdash c \rrbracket^{\text{Set}} \rho = C$ for all ρ , i.e., can take c to denote a constant C . We then get a free theorem whose conclusion is $\text{fold}_H B \circ G \mu H \text{ in}_H = G \llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}} B$.

Can do Hinze's bit-reversal protocol in our system with

cat $:: \alpha; \emptyset \vdash \text{Nat}^0(\text{Nat}^0(\text{List } \alpha)(\text{List } \alpha))(\text{List } \alpha)$
 zip $:: \alpha; \emptyset \vdash \text{Nat}^0(\text{Nat}^0(\text{List } \alpha)(\text{List } \beta))(\text{List } (\alpha \times \beta))$
 ?

THEOREM 44. Let $\emptyset; \phi, \alpha \vdash F : \mathcal{F}$, let $\emptyset; \alpha \vdash K : \mathcal{F}$, and let $\phi; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^\alpha F(\phi\alpha))(\text{Nat}^\alpha \mathbb{1}(\phi\alpha))$. If we let $H : [\text{Set}, \text{Set}] \rightarrow [\text{Set}, \text{Set}]$ be defined by

$$H f x = \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Set}}[\phi := f][\alpha := x]$$

and let

$$G = \llbracket \phi; \emptyset \mid \emptyset \vdash g : \text{Nat}^0(\text{Nat}^\alpha F(\phi\alpha))(\text{Nat}^\alpha \mathbb{1}(\phi\alpha)) \rrbracket^{\text{Set}}$$

then we have that, for every $B \in H[\llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}} \rightarrow \llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}}$,

$$\text{fold}_H B (G \mu H \text{ in}_H) = G \llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}} B$$

PROOF. We first note that the type of g is well-formed since $\emptyset; \phi, \alpha \vdash F : \mathcal{F}$ so our promotion theorem gives that $\phi; \alpha \vdash F : \mathcal{F}$, and $\phi; \alpha \vdash \phi\alpha : \mathcal{F}$, so that $\phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) : \mathcal{T}$ and $\phi; \emptyset \vdash \text{Nat}^\alpha \mathbb{1}(\phi\alpha) : \mathcal{T}$. Then $\phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) : \mathcal{F}$ and $\phi; \emptyset \vdash \text{Nat}^\alpha \mathbb{1}(\phi\alpha) : \mathcal{F}$ also hold, and, finally, $\phi; \emptyset \vdash \text{Nat}^0(\text{Nat}^\alpha F(\phi\alpha))(\text{Nat}^\alpha \mathbb{1}(\phi\alpha)) : \mathcal{T}$

Theorem 37 gives that, for any relation environment ρ and any $(a, b) \in \llbracket \phi, \alpha; \emptyset \vdash \emptyset \rrbracket^{\text{Rel}} \rho = 1$, eliding the only possible instantiations of a and b gives that

$$\begin{aligned} (G(\pi_1 \rho), G(\pi_2 \rho)) &\in \llbracket \phi; \emptyset \vdash \text{Nat}^0(\text{Nat}^\alpha F(\phi\alpha))(\text{Nat}^\alpha \mathbb{1}(\phi\alpha)) \rrbracket^{\text{Rel}} \rho \\ &= \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) \rrbracket^{\text{Rel}} \rho \rightarrow \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha \mathbb{1}(\phi\alpha) \rrbracket^{\text{Rel}} \rho \\ &= \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) \rrbracket^{\text{Rel}} \rho \rightarrow (\lambda A. 1 \Rightarrow \lambda A. (\rho\phi)A) \\ &= \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) \rrbracket^{\text{Rel}} \rho \rightarrow (1 \Rightarrow \rho\phi) \\ &= \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) \rrbracket^{\text{Rel}} \rho \rightarrow \rho\phi \end{aligned}$$

So if $(A, B) \in \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) \rrbracket^{\text{Rel}} \rho$ then

$$(G(\pi_1 \rho) A, G(\pi_2 \rho) B) \in \rho\phi$$

Now note that

$$\llbracket \vdash \text{fold}_F^K : \text{Nat}^0(\text{Nat}^\alpha F[\phi := K] K) (\text{Nat}^\alpha ((\mu\phi. \lambda\alpha. F)\alpha) K) \rrbracket^{\text{Set}} = \text{fold}_H$$

and consider the instantiation

$$\begin{aligned} A &= \text{in}_H : H(\mu H) \Rightarrow \mu H \\ B &: H[\llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}} \Rightarrow \llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}} \\ \rho\phi &= \langle \text{fold}_H B \rangle \quad \text{a graph of a natural transformation, defined in Enrico's notes} \end{aligned}$$

(Note that all the types here are well-formed.) This gives

$$\begin{aligned} \pi_1 \rho\phi &= \mu H \\ \pi_2 \rho\phi &= \llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}} \\ \rho\phi &: \text{Rel}(\pi_1 \rho\phi, \pi_2 \rho\phi) \\ A &: \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) \rrbracket^{\text{Set}}(\pi_1 \rho) \\ B &: \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi\alpha) \rrbracket^{\text{Set}}(\pi_2 \rho) \end{aligned}$$

since

$$\begin{aligned}
 A = in_H & : H(\mu H) \Rightarrow \mu H \\
 &= \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Set}}[\phi := \mu \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Set}}] \Rightarrow \mu \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Set}} \\
 &= \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Set}}(\pi_1 \rho) \Rightarrow \llbracket \emptyset; \phi, \alpha \vdash \phi \alpha \rrbracket^{\text{Set}}(\pi_1 \rho) \\
 &= \llbracket \phi; \alpha \vdash F \rrbracket^{\text{Set}}(\pi_1 \rho) \Rightarrow \llbracket \phi; \alpha \vdash \phi \alpha \rrbracket^{\text{Set}}(\pi_1 \rho) \quad \text{Daniel's trick; now a theorem} \\
 &= \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi \alpha) \rrbracket^{\text{Set}}(\pi_1 \rho)
 \end{aligned}$$

We also have

$$\begin{aligned}
 (A, B) = (in_H, B) & \in \llbracket \phi; \emptyset \vdash \text{Nat}^\alpha F(\phi \alpha) \rrbracket^{\text{Rel}} \rho \\
 &= \lambda A. \llbracket \phi; \alpha \vdash F \rrbracket^{\text{Rel}} \rho[\alpha := A] \Rightarrow \lambda A. (\rho \phi) A \\
 &= \lambda A. \llbracket \phi; \alpha \vdash F \rrbracket^{\text{Rel}}[\phi := \langle fold_H B \rangle][\alpha := A] \Rightarrow \langle fold_H B \rangle \\
 &= \lambda A. \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Rel}}[\phi := \langle fold_H B \rangle][\alpha := A] \Rightarrow \langle fold_H B \rangle \quad \text{Daniel's trick; now a theorem} \\
 &= \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Rel}} \langle fold_H B \rangle \Rightarrow \langle fold_H B \rangle \\
 &= \langle \llbracket \emptyset; \phi, \alpha \vdash F \rrbracket^{\text{Set}}(fold_H B) \rangle \Rightarrow \langle fold_H B \rangle \quad \text{Graph Lemma} \\
 &= \langle map_H(fold_H B) \rangle \Rightarrow \langle fold_H B \rangle
 \end{aligned}$$

since if $(x, y) \in \langle map_H(fold_H B) \rangle$, i.e., if $map_H(fold_H B)x = y$, then $fold_H B(in_H x) = B y = B(map_H(fold_H B)x)$ by the definition of $fold_H$ as a (indeed, the unique) morphism from in_H to B . Thus,

$$(G(\pi_1 \rho) A, G(\pi_2 \rho) B) \in \langle fold_H B \rangle$$

i.e.,

$$fold_H B(G(\pi_1 \rho) in_H) = G(\pi_2 \rho) B$$

Since ϕ is the only free variable in G , this simplifies to

$$fold_H B(G \mu H in_H) = G \llbracket \emptyset; \alpha \vdash K \rrbracket^{\text{Set}} B$$

□

7 CONCLUSION

Can do everything in abstract locally presentable cartesian closed category.

Give definitions for arb lpccc, but compute free theorems in Set/Rel.

Future Work (in progress): extend calculus to GADTs

Add more polymorphisms (all forall), even though most free theorems only use one level (or maybe two, like short cut).

fixed points at term level ala Pitts

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