Abstract

This (online only) document contains full proofs and derivations of all of the theorems for the soundness of PEC semantics. It is not intended to have the same polish as the dissertation.

Contents

Chapter 1

Language Definition

1.1 Terms

$$
\begin{aligned}
v ::= & \; x \\
& \mid \lambda x : A . v \\
& \mid \mathtt{k}^{A} \\
& \mid \mathtt{()} \\
& \mid \mathtt{true} \mid \mathtt{false} \\
& \mid \Lambda \alpha . v \\
& \mid v \; \epsilon \\
& \mid \mathtt{if}_{A} \; v \; \mathtt{then} \; v_1 \; \mathtt{else} \; v_2 \\
& \mid v_1 \; v_2 \\
& \mid \mathtt{do} \; x \leftarrow v_1 \; \mathtt{in} \; v_2 \\
& \mid \mathtt{return} \; v
\end{aligned}
$$

1.2 Type System

1.2.1 Ground Effects

The effects should form a monotonous, partially-ordered monoid $(E, \cdot, \mathtt{1}, \leq)$ with ground elements e.

1.2.2 Effect Po-Monoid Under an Effect Environment

Derive a new Po-Monoid for each Φ:

$$(E_\Phi, \cdot_\Phi, \mathtt{1}, \leq_\Phi) \tag{1.1}$$

Where meta-variables, ϵ, range over E_Φ Where

$$E_\Phi = E \cup \{\alpha \mid \alpha \in \Phi\} \tag{1.2}$$

And

$$\frac{\epsilon_3 = \epsilon_1 \cdot \epsilon_2}{\epsilon_3 = \epsilon_1 \cdot_\Phi \epsilon_2} \tag{1.3}$$

Otherwise, $\cdot_\Phi$ is symbolic in nature.

$$\epsilon_1 \leq_\Phi \epsilon_2 \Leftrightarrow \forall \sigma \downarrow . \epsilon_1[\sigma \downarrow] \leq \epsilon_2[\sigma \downarrow] \tag{1.4}$$

Where $\sigma \downarrow$ denotes any ground-substitution of Φ. That is any substitution of all effect variables in Φ to ground effects. Where it is obvious from the context, I shall use $\leq$ instead of $\leq_\Phi$.

1.2.3 Types

Ground Types There exists a set γ of ground types, including `Unit`, `Bool`

Term Types

$$A, B, C ::= \gamma \mid A \to B \mid \mathtt{M}_\epsilon A \mid \forall \alpha . A$$

1.2.4 Type and Effect Environments

A type environment is a snoc-list of term-variable, type pairs, $G ::= \diamond \mid \Gamma, x : A$. An effect environment is a snoc-list of effect variables.

$\Phi ::= \diamond \mid \Phi, \alpha$

Domain Function on Type Environments

- $\mathtt{dom}(\diamond) = \emptyset$
- $\mathtt{dom}(\Gamma, x : A) = \mathtt{dom}(\Gamma) \cup \{x\}$

Membership of Effect Environments Informally, $\alpha \in \Phi$ if α appears in the list represented by Φ.

`Ok` Predicate On Effect Environments

- (E-Env-Nil) $\dfrac{}{\diamond \ \mathtt{Ok}}$
- (E-Env-Extend) $\dfrac{\Phi \ \mathtt{Ok}}{\Phi, \alpha \ \mathtt{Ok}}$ (if $\alpha \notin \Phi$)

Wellformedness of effects We define a relation $\Phi \epsilon$.

- (E-Ground) $\dfrac{\Phi \ \mathtt{Ok}}{\Phi e}$
- (Var) $\dfrac{\Phi, \alpha \ \mathtt{Ok}}{\Phi, \alpha \alpha}$
- (E-Weaken) $\dfrac{\Phi \alpha}{\Phi, \beta \alpha}$ (if $\alpha \neq \beta, b \notin \Phi$)
- (E-Compose) $\dfrac{\Phi \epsilon_1 \qquad \Phi \epsilon_2}{\Phi \epsilon_1 \cdot \epsilon_2}$

Wellformedness of Types We define a relation ΦA on types.

- (T-Ground) $\dfrac{}{\Phi\gamma}$

- (T-Fn) $\dfrac{\Phi A \qquad \Phi B}{\Phi A \to B}$

- (T-Effect) $\dfrac{\Phi A \qquad \Phi\epsilon}{\Phi \mathtt{M}_\epsilon A}$

- (T-Quantification) $\dfrac{\Phi, \alpha A}{\Phi \forall\alpha.A}$

Ok Predicate on Type Environments We now define a predicate on type environments and effect environments: $\Phi \vdash \Gamma\ \mathtt{Ok}$

- (Env-Nil) $\dfrac{}{\Phi \vdash \diamond\ \mathtt{Ok}}$

- (Env-Extend) $\dfrac{\Phi \vdash \Gamma\ \mathtt{Ok} \qquad x \notin \mathtt{dom}(\Gamma) \qquad \Phi A}{\Phi \vdash \Gamma, x\colon A\ \mathtt{Ok}}$

1.2.5 Subtyping

There exists a subtyping partial-order relation $\leq:_\gamma$ over ground types that is:

- (S-Reflexive) $\dfrac{}{A \leq:_\gamma A}$

- (S-Transitive) $\dfrac{A \leq:_\gamma B \qquad B \leq:_\gamma C}{A \leq:_\gamma C}$

We extend this relation with the (Fn) and (Quantification) subtyping rules to yield the full subtyping relation under an effect environment, Φ, $\leq:_\Phi$

- (S-Ground) $\dfrac{A \leq:_\gamma B}{A \leq:_\Phi B}$

- (S-Fn) $\dfrac{A \leq:_\Phi A' \qquad B' \leq:_\Phi B}{A' \to B' \leq:_\Phi A \to B}$

- (S-Quantification) $\dfrac{A \leq:_\Phi A' \qquad a \notin \Phi}{\forall\alpha.A \leq:_\Phi \forall a.A'}$

- (S-Effect) $\dfrac{A \leq:_\Phi B \qquad \epsilon_1 \leq_\Phi \epsilon_2}{\mathtt{M}_{\epsilon_1} A \leq:_\Phi \mathtt{M}_{\epsilon_2} B}$

1.2.6 Type Rules

- (Const) $\dfrac{\Phi \vdash \Gamma\ \ \texttt{Ok} \qquad \Phi A}{\Phi \mid \Gamma \vdash \texttt{k}^{A} \colon A}$
- (Unit) $\dfrac{\Phi \vdash \Gamma\ \ \texttt{Ok}}{\Phi \mid \Gamma \vdash \texttt{()} \colon \texttt{Unit}}$
- (True) $\dfrac{\Phi \vdash \Gamma\ \ \texttt{Ok}}{\Phi \mid \Gamma \vdash \texttt{true} \colon \texttt{Bool}}$
- (False) $\dfrac{\Phi \vdash \Gamma\ \ \texttt{Ok}}{\Phi \mid \Gamma \vdash \texttt{false} \colon \texttt{Bool}}$
- (Var) $\dfrac{\Phi \vdash \Gamma, x \colon A\ \ \texttt{Ok}}{\Phi \mid \Gamma, x \colon A \vdash x \colon A}$
- (Weaken) $\dfrac{\Phi \mid \Gamma \vdash x \colon A \qquad \Phi B}{\Phi \mid \Gamma, y \colon B \vdash x \colon A}$ (if $x \neq y, y \notin \texttt{dom}(\Gamma)$)
- (Fn) $\dfrac{\Phi \mid \Gamma, x \colon A \vdash v \colon B}{\Phi \mid \Gamma \vdash \lambda x \colon A.v : A \to B}$
- (Subtype) $\dfrac{\Phi \mid \Gamma \vdash v \colon A \qquad A {\leq :}_{\Phi} B}{\Phi \mid \Gamma \vdash v \colon B}$
- (Effect-Gen) $\dfrac{\Phi, \alpha \mid \Gamma \vdash v \colon A}{\Phi \mid \Gamma \vdash \Lambda\alpha.v \colon \forall\alpha.A}$
- (Effect-Spec) $\dfrac{\Phi \mid \Gamma \vdash v \colon \forall\alpha.A \qquad \Phi\epsilon}{\Phi \mid \Gamma \vdash v\ \epsilon \colon A[\epsilon/\alpha]}$
- (Return) $\dfrac{\Phi \mid \Gamma \vdash v \colon A}{\Phi \mid \Gamma \vdash \texttt{return}\ v : \texttt{M}_{1} A}$
- (Apply) $\dfrac{\Phi \mid \Gamma \vdash v_1 \colon A \to \texttt{M}_{\epsilon} B \qquad \Phi \mid \Gamma \vdash v_2 \colon A}{\Phi \mid \Gamma \vdash v_1\ v_2 \colon \texttt{M}_{\epsilon} B}$
- (If) $\dfrac{\Phi \mid \Gamma \vdash v \colon \texttt{Bool} \qquad \Phi \mid \Gamma \vdash v_1 \colon A \qquad \Phi \mid \Gamma \vdash v_2 \colon A}{\Phi \mid \Gamma \vdash \texttt{if}_{A}\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2 : A}$
- (Bind) $\dfrac{\Phi \mid \Gamma \vdash v_1 \colon \texttt{M}_{\epsilon_1} A \qquad \Phi \mid \Gamma, x \colon A \vdash v_2 \colon \texttt{M}_{\epsilon_2} B}{\Phi \mid \Gamma \vdash \texttt{do}\ x \leftarrow v_1\ \texttt{in}\ v_2 : \texttt{M}_{\epsilon_1 \cdot \epsilon_2} B}$

1.2.7 Ok Lemma

If $\Phi \mid \Gamma \vdash v \colon A$ then $\Phi \vdash \Gamma\ \ \texttt{Ok}$.

Proof If $\Gamma, x \colon A\ \ \texttt{Ok}$ then by inversion. $\Gamma\ \ \texttt{Ok}$. Only the type rule *(Weaken)* adds terms to the environment from its preconditions to its post-condition and it does so in an `Ok` preserving way. Any type derivation tree has at least one leaf. All leaves are axioms which require $\Phi \vdash \Gamma\ \ \texttt{Ok}$. And all non axiom derivations preserve the `Ok` property.

Chapter 2

Preliminaries

2.1 Base Category Requirements

There are 2 distinct objects in the base category, $\mathbb{C}$:

- U - The kind of `Effect`
- `1` - A terminal object

And we have finite products on U.

- $U^0 = \mathtt{1}$
- $U^{n+1} = U^n \times U$

We also have the following natural operations on morphisms in $\mathbb{C}$.
Let $I = U^n$.

- $\mathtt{Mul}_I : \mathbb{C}(I, U) \times \mathbb{C}(I, U) \to \mathbb{C}(I, U)$ - Generates multiplication of effects.

With naturality conditions which mean, for $\theta : U^m \to U^n (I' \to I)$,

- $\mathtt{Mul}_I(\phi, \psi) \circ \theta = \mathtt{Mul}_{I'}(\phi \circ \theta, \psi \circ \theta)$

2.2 Wellformedness

Each instance of the wellformedness relation on effects, $\Phi\epsilon$ has a denotation in $\mathbb{C}$:

$$[\![\Phi \vdash \epsilon \colon \mathtt{Effect}]\!] : I \to U \tag{2.1}$$

It should also be the case that

$$\mathtt{Mul}_I([\![\Phi \vdash \epsilon_1 \colon \mathtt{Effect}]\!], [\![\Phi \vdash \epsilon_2 \colon \mathtt{Effect}]\!]) = [\![\Phi \vdash \epsilon_1 \cdot \epsilon_2 \colon \mathtt{Effect}]\!] \in \mathbb{C}(I, U) \tag{2.2}$$

That is, $\mathtt{Mul}_I$ should be have identity $[\![\Phi \vdash \mathtt{1} \colon \mathtt{Effect}]\!]$ and be associative.

2.3 Substitution and Weakening of the Effect Environment

2.3.1 Denotations

For each instance of the wellformedness relation on substitution of effects $\Phi' \vdash \sigma\colon\Phi$, there exists a denotation in $\mathbb{C}$:

$$[\![\Phi' \vdash \sigma\colon\Phi]\!] : I' \to I \tag{2.3}$$

For each instance of the well formed weakening relation on effect-variable environments, $\omega\colon\Phi' \triangleright \Phi$ there exists a denotation in $\mathbb{C}$:

$$[\![\omega\colon\Phi' \triangleright \Phi]\!] : I' \to I \tag{2.4}$$

.

2.4 Fibre Categories

Each set of morphisms $\mathbb{C}(I)$ corresponds to a semantic category (S-category). That is, a category satisfying all the properties needed for the non-polymorphic language:

- Cartesian Closed
- Co-product of the terminal object with itself $(\mathtt{1} + \mathtt{1})$
- Ground morphisms for each ground constant $(\mathtt{k}^A : \mathtt{1} \to A)$
- Partial order morphisms on ground types $([\![A \leq:_\gamma]\!]B)$
- A strong, monad, graded by the po-monoid $(\mathbb{C}(I, U), \mathtt{Mul}_I, \leq_\Phi, [\![\mathtt{1}]\!])$.

2.5 Re-Indexing Functors

TODO: Use this section for the S-Preservation definition appendix For each morphism $f : I' \to I$ in $\mathbb{C}$, there should be a co-variant, re-indexing functor $f^* : \mathbb{C}(I) \to \mathbb{C}(I')$, which is S-preserving. That is, it preserves the S-category structure of $\mathbb{C}(I)$. (See below).

$(-)^*$ should be a contra-variant functor in its $\mathbb{C}$ argument and co-variant in its right argument.

- $(g \circ f)^*(a) = f^*(\gamma^*(a))$
- $\mathtt{Id}_I^*(a) = a$
- $f^*(\mathtt{Id}_A) = \mathtt{Id}_{f^*(A)}$
- $f^*(a \circ b) = f^*(a) \circ f^*(b)$

2.5.1 Preserves Ground Types

If $[\![\gamma]\!] \in \mathtt{obj}\ \mathbb{C}(I)$ then $f^*[\![\gamma]\!] = [\![\gamma]\!] \in \mathtt{obj}\ \mathbb{C}(I')$

2.5.2 f^* Preserves Products

If $\langle g, h\rangle : \mathbb{C}(I)(Z, X \times Y)$ Then

$$\begin{aligned} f^*(X \times Y) &= f^*(X) \times f^*(Y) \\ f^*(\langle g, h\rangle) &= \langle f^*(g), f^*h\rangle && : \mathbb{C}(I')(f^*Z, f^*(X) \times f^*(Y)) \\ f^*(\pi_1) &= \pi_1 && : \mathbb{C}(I')(f^*(X) \times f^*(Y), f^*(X)) \\ f^*(\pi_2) &= \pi_2 && : \mathbb{C}(I')(f^*(X) \times f^*(Y), f^*(Y)) \end{aligned}$$

2.5.3 f^* Preserves Terminal Object

If $\mathtt{Id}_A : \mathbb{C}(I)(A, \mathtt{1})$ Then

$$\begin{aligned} f^*(\mathtt{1}) &= \mathtt{1} \\ f^*(\langle\rangle_A) &= \langle\rangle_{f^*(A)} && : \mathbb{C}(I')(f^*A, \mathtt{1}) \end{aligned}$$

2.5.4 f^* Preserves Exponentials

$$\begin{aligned} f^*(Z^X) &= (f^*(Z))^{(f^*(X))} \\ f^*(\mathtt{app}) &= \mathtt{app} && : \mathbb{C}(I')(f^*(Z^X) \times f^*(X), f^*(Z)) \\ f^*(\mathtt{cur}(g)) &= \mathtt{cur}(f^*(g)) && : \mathbb{C}(I')(f^*(Y) \times f^*(X), f^*(Z)^{f^*(X)}) \end{aligned}$$

2.5.5 f^* Preserves Co-product on Terminal

$$\begin{aligned} f^*(\mathtt{1}+\mathtt{1}) &= \mathtt{1}+\mathtt{1} \\ f^*(\mathtt{inl}) &= \mathtt{inl} && : \mathbb{C}(I')(\mathtt{1}, \mathtt{1}+\mathtt{1}) \\ f^*(\mathtt{inr}) &= \mathtt{inr} && : \mathbb{C}(I')(\mathtt{1}, \mathtt{1}+\mathtt{1}) \\ f^*([g, h]) &= [f^*(g), f^*(h)] && : \mathbb{C}(I')(\mathtt{1}+\mathtt{1}, f^*(Z)) \end{aligned}$$

2.5.6 f^* Preserves Graded Monad

$$\begin{aligned} f^*(T_\epsilon A) &= T_{f^*(\epsilon)} f^*(A) && : \mathbb{C}(I') \\ f^*(\eta_A) &= \eta_{f^*(A)} && : \mathbb{C}(I')(f^*(A), f^*(T_{\mathbf{1}} A)) \\ f^*(\mu_{\epsilon_1,\epsilon_2,A}) &= \mu_{f^*(\epsilon_1), f^*(\epsilon_2), f^*(A)} && : \mathbb{C}(I')(f^*(T_{\epsilon_1} T_{\epsilon_2} A), f^*(T_{\epsilon_1\cdot\epsilon_2} A)) \end{aligned}$$

2.5.7 f^* and Effects

$$\begin{aligned} f^*(\mathtt{1}) &= \mathtt{1} \quad \text{The unit effect} \\ f^*(\epsilon_1 \cdot \epsilon_2) &= f^*(\epsilon_1) \cdot f^*(\epsilon_2) \quad \text{Multiplication} \end{aligned}$$

This is done By

$$f^*[\![\Phi \vdash \epsilon \colon \mathtt{Effect}]\!] = [\![\Phi \vdash \epsilon \colon \mathtt{Effect}]\!] \circ f$$

2.5.8 f^* Preserves Tensor Strength

$$f^*(\mathtt{t}_{\epsilon,A,B}) = \mathtt{t}_{f^*(\epsilon),f^*(A),f^*(B)} \qquad : \mathbb{C}(I')(f^*(A \times T_\epsilon B), f^*(T_\epsilon(A \times B)))$$

2.5.9 f^* Preserves Ground Constants

For each ground constant $[\![\mathtt{k}^A]\!]$ in $\mathbb{C}(I)$,

$$f^*([\![\mathtt{k}^A]\!]) = \mathtt{k}^{f^*(A)} : \mathbb{C}(I')(\mathtt{1}, f^*(A))$$

2.5.10 f^* Preserves Ground Subeffecting

For ground effects e_1, e_2 such that $e_1 \leq e_2$

$$f^*(e) = e : \mathbb{C}(I')$$
$$f^*[\![\epsilon_1 \leq e_2]\!]_A = [\![e_1 \leq e_2]\!]_{f^*(A)} : \mathbb{C}(I')f^*(T_{e_1}A), f^*(T_{e_2}A)$$

2.5.11 f^* Preserves Ground Subtyping

For ground types γ_1, γ_2 such that $\gamma_1 \leq :_\gamma \gamma_2$

$$f^*\gamma = \gamma : \mathbb{C}(I')(\mathtt{1}, \gamma)$$
$$f^*([\![\gamma_1 \leq :_\gamma \gamma_2]\!]) = [\![\gamma_1 \leq :_\gamma \gamma_2]\!] \qquad : \mathbb{C}(I')(\gamma_1, \gamma_2)$$

2.6 The $\forall_I$ functor

We expand $\forall_I : \mathbb{C}(I \times U) \to \mathbb{C}(I)$ to be a functor which is right adjoint to the re-indexing functor π_1^*.

$$\overline{(\_)} : \mathbb{C}(I \times U)(\pi_1^* A, B) \leftrightarrow \mathbb{C}(I)(A, \forall_I B) : \widehat{(\_)} \tag{2.5}$$

For $A \in \mathtt{obj}\ \mathbb{C}(I)$, $B \in \mathtt{obj}\ \mathbb{C}(I \times U)$.

Hence the action of $\forall_I$ on a morphism $l : A \to A'$ is as follows:

$$\forall_I(l) = \overline{l \circ \boldsymbol{\epsilon}_A} \tag{2.6}$$

Where $\epsilon_A : \mathbb{C}(I \times U)(\pi_1^* \forall_I A \to A)$ is the co-unit of the adjunction.

2.6.1 Beck Chevalley Condition

We need to be able to commute the $\forall_I$ functor with re-indexing functors. A natural way to do this is:

$$\theta^* \circ \forall_I = \forall_{I'} \circ (\theta \times \mathtt{Id}_U)^*$$

We shall also require that the canonical natural-transformation between these functors is the identity. That is, $\overline{(\theta \times \mathtt{Id}_U)^*(\boldsymbol{\epsilon})} = \mathtt{Id} : \theta^* \circ \forall_I \to \forall_{I'} \circ (\theta \times \mathtt{Id}_U)^* \in \mathbb{C}(I')$

This shall be called the Beck-Chevalley condition.

2.7 Naturality Corollaries

Here are some simple corollaries of the adjunction between π_1^* and $\forall_I$.

2.7.1 Naturality

By the definition of an adjunction:

$$\overline{f \circ \pi_1^*(n)} = \overline{f} \circ n \tag{2.7}$$

2.7.2 $\overline{(-)}$ and Re-indexing Functors

By assuming the Beck-Chevalley condition that:

$$\overline{(\theta \times \mathtt{Id}_U)^*(\boldsymbol{\epsilon})} = \mathtt{Id} : \theta^* \circ \forall_I \to \forall_{I'} \circ (\theta \times \mathtt{Id}_U)^* \tag{2.8}$$

We then have:

$$\begin{aligned}
\theta^*\boldsymbol{\eta}_A : \quad & \theta^* A \to \theta^* \circ \forall_I \circ \pi_1^* A \\
\theta^*\boldsymbol{\eta} =& \overline{(\theta \times \mathtt{Id}_U)^*(\boldsymbol{\epsilon}_{\pi_1^*})} \circ \theta^*\boldsymbol{\eta} \\
=& (\forall_{I'} \circ (\theta \times \mathtt{Id}_U)^*)(\boldsymbol{\epsilon}_{\pi_1^*}) \circ \boldsymbol{\eta}_{(\forall_{I'} \circ (\theta \times \mathtt{Id}_U)^*) \circ \pi_1^*} \circ \theta^*\boldsymbol{\eta} \\
=& (\forall_{I'} \circ (\theta \times \mathtt{Id}_U)^*)(\boldsymbol{\epsilon}_{\pi_1^*}) \circ \boldsymbol{\eta}_{\theta^* \circ \forall_I \circ \pi_1^*} \circ \theta^*\boldsymbol{\eta} \\
=& (\forall_{I'} \circ (\theta \times \mathtt{Id}_U)^*)(\boldsymbol{\epsilon}_{\pi_1^*}) \circ (\theta^* \circ \forall_I \circ \pi_1^*)\boldsymbol{\eta} \circ \boldsymbol{\eta}_{(\theta \times \mathtt{Id}_U)^*} \\
=& (\theta^* \circ \forall_I)(\boldsymbol{\epsilon}_{\pi_1^*} \circ \pi_1^*\boldsymbol{\eta}) \circ \boldsymbol{\eta}_{(\theta \times \mathtt{Id}_U)^*} \\
=& (\theta^* \circ \forall_I)(\mathtt{Id}) \circ \boldsymbol{\eta}_{(\theta \times \mathtt{Id}_U)^*} \\
=& \boldsymbol{\eta}_{(\theta \times \mathtt{Id}_U)^*}
\end{aligned}$$

$$\begin{aligned}
\theta^*(\overline{f}) &= \theta^*(\forall_I(f) \circ \eta_A) \\
&= \theta^*(\forall_I(f)) \circ \theta^*(\eta_A) \\
&= (\forall_{I'} \circ (\theta \times \mathtt{Id}_U)^*) f \circ \boldsymbol{\eta}_{(\theta \times \mathtt{Id}_U)^* A} \\
&= \overline{(\theta \times \mathtt{Id}_U)^* f}
\end{aligned}$$

2.7.3 $(\hat{-})$ and Re-Indexing Functors

$$
\begin{aligned}
\theta^*(\langle \mathtt{Id}_I, \rho\rangle^*(\widehat{m})) &= (\langle \mathtt{Id}_I, \rho\rangle \circ \theta)^*(\widehat{m}) \\
&= ((\theta \times \mathtt{Id}_U) \circ \langle \mathtt{Id}_I, \rho\rangle)^*(\widehat{m}) \\
&= \langle \mathtt{Id}_I, \rho \circ \theta\rangle^*(\theta \times \mathtt{Id}_U)^*(\widehat{m}) \\
&= \langle \mathtt{Id}_I, \theta^*\rho\rangle^*(\theta^*(\widehat{m}))
\end{aligned}
$$

2.7.4 Pushing Morphisms into f^*

$$
\begin{aligned}
\langle \mathtt{Id}_I, \rho\rangle^*(\widehat{m}) \circ n &= \langle \mathtt{Id}_I, \rho\rangle^*(\widehat{m}) \circ \langle \mathtt{Id}_I, \rho\rangle^*\pi_1^*(n) \\
&= \langle \mathtt{Id}_I, \rho\rangle^*(\widehat{m} \circ \pi_1^*(n)) \\
&= \langle \mathtt{Id}_I, \rho\rangle^*(\widehat{m \circ n})
\end{aligned}
$$

Chapter 3

Weakenings and Substitutions

3.1 Effect-Environment Weakenings

Introduce a relation $\omega\colon \Phi' \triangleright \Phi$ relating effect-variable environments.

3.1.1 Relation

- (E-Id) $\dfrac{\Phi \ \mathtt{Ok}}{\iota\colon \Phi \triangleright \Phi}$
- (E-Project) $\dfrac{\omega\colon \Phi' \triangleright \Phi}{\omega\pi\colon (\Phi', \alpha) \triangleright \Phi}$
- (E-Extend) $\dfrac{\omega\colon \Phi' \triangleright \Phi}{\omega\times\colon (\Phi', \alpha) \triangleright (\Phi, \alpha)}$

3.1.2 Weakening Properties

Property 3.1.1 (Weakening Preserves Ok).

$$\omega\colon \Phi' \triangleright \Phi \wedge \Phi \ \mathit{Ok} \Rightarrow \Phi' \ \mathit{Ok} \tag{3.1}$$

Proof:

Case: ι

$$\Phi \ \mathtt{Ok} \wedge \iota\colon \Phi \triangleright \Phi \Rightarrow \Phi \ \mathtt{Ok}$$

Case: $\omega\pi$ By inversion,

$$\omega\colon \Phi' \triangleright \Phi \wedge \alpha \notin \Phi' \tag{3.2}$$

So, by induction, $\Phi' \ \mathtt{Ok}$ and hence $(\Phi', \alpha) \ \mathtt{Ok}$

Case: $\omega\times$ By inversion,

$$\omega\colon \Phi' \triangleright \Phi \wedge \alpha \notin \Phi' \tag{3.3}$$

So

$$\begin{aligned}(\Phi, \alpha)\ \texttt{Ok} &\Rightarrow \Phi\ \texttt{Ok}\\ &\Rightarrow \Phi'\ \texttt{Ok}\\ &\Rightarrow (\Phi', \alpha)\ \texttt{Ok}\end{aligned}$$

Property 3.1.2 (Domain Lemma)**. 3.1.3 Domain Lemma**

$$\omega\colon \Phi' \triangleright \Phi \Rightarrow (\alpha \notin \Phi' \Rightarrow \alpha \notin \Phi)$$

Proof: By trivial Induction.

3.2 Effect-Environment Substitutions

3.2.1 Snoc Lists

Effect-Environment substitutions may be represented as a snoc-list of variable-effect pairs.

$$\sigma ::= \diamond \mid \sigma, \alpha := \epsilon$$

3.2.2 Wellformedness

For any two effect-variable environments, and a substitution, define the wellformedness relation:

$$\Phi' \vdash \sigma\colon \Phi \tag{3.4}$$

- (E-Nil) $\dfrac{\Phi'\ \texttt{Ok}}{\Phi' \vdash \diamond\colon \diamond}$
- (Eq-Subtype) $\dfrac{\Phi' \vdash \sigma\colon \Phi \qquad \Phi' \epsilon \qquad \alpha \notin \Phi}{\Phi' \vdash \sigma, \alpha := \epsilon\colon (\Phi, \alpha)}$

3.2.3 Actions

On Effects

Define the action of applying an effect substitution to an effect symbol:

$$\sigma(\epsilon) \tag{3.5}$$

$$
\begin{aligned}
\sigma(e) &= e \\
\sigma(\epsilon_1 \cdot \epsilon_2) &= (\sigma(\epsilon_1)) \cdot (\sigma(\epsilon_2)) \\
\diamond(\alpha) &= \alpha \\
(\sigma, \beta{:}= \epsilon)(\alpha) &= \sigma(\alpha) \\
(\sigma, \alpha{:}= \epsilon)(\alpha) &= \epsilon
\end{aligned}
$$

On Types

Define the action of applying an effect substitution, σ to a type A as:

$$A[\sigma]$$

Defined as so

$$
\begin{aligned}
\gamma[\sigma] &= \gamma \\
(A \to B)[\sigma] &= (A[\sigma]) \to (B[\sigma]) \\
(\mathtt{M}_\epsilon A)[\sigma] &= \mathtt{M}_{\sigma(\epsilon)}(A[\sigma]) \\
(\forall \alpha. A)[\sigma] &= \forall \alpha. (A[\sigma]) \quad \text{If } \alpha \# \sigma
\end{aligned}
$$

On Term Environments

Define the action of effect substitution on type environments:

$$\Gamma[\sigma]$$

Defined as so:

$$
\begin{aligned}
\diamond[\sigma] &= \diamond \\
(\Gamma, x{:}\, A)[\sigma] &= (\Gamma[\sigma], x : (A[\sigma]))
\end{aligned}
$$

On Terms

Define the action of effect-environment substitution on terms:

$$
\begin{aligned}
x[\sigma] &= x \\
\mathtt{k}^{A}[\sigma] &= \mathtt{k}^{(A[\sigma])} \\
(\lambda x\colon A.v\ )[\sigma] &= \lambda x\colon (A[\sigma]).(v[\sigma]) \\
(\mathtt{if}_{A}\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2\ )[\sigma] &= \mathtt{if}_{(A[\sigma])}\ v[\sigma]\ \mathtt{then}\ v_1[\sigma]\ \mathtt{else}\ v_2[\sigma] \\
(v_1\ v_2)[\sigma] &= (v_1[\sigma])\ v_2[\sigma] \\
(\mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2\ )[\sigma] &= \mathtt{do}\ x \leftarrow (v_1[\sigma])\ \mathtt{in}\ (v_2[\sigma]) \\
(\Lambda\alpha.v)[\sigma] &= \Lambda\alpha.(v[\sigma]) \quad \text{If } \alpha\#\sigma \\
(v\ \epsilon)[\sigma] &= (v[\sigma])\ \sigma(\epsilon)
\end{aligned}
$$

3.2.4 Properties

Property 3.2.1 (Wellformedness). *If $\Phi' \vdash \sigma\colon \Phi$ then Φ' $\mathtt{Ok}$ (By the Nil case) and Φ $\mathtt{Ok}$ Since each use of the extend case preserves $\mathtt{Ok}$.*

Property 3.2.2 (Weakening). *If $\Phi' \vdash \sigma\colon \Phi$ then $\omega\colon \Phi' \triangleright \Phi' \implies \Phi'' \vdash \sigma\colon \Phi$ since $\Phi'\epsilon \implies \Phi''\epsilon$ and Φ' $\mathtt{Ok} \implies \Phi''$ $\mathtt{Ok}$*

Property 3.2.3 (Extension). *If $\Phi' \vdash \sigma\colon \Phi$ then*

$$\alpha \notin \Phi \wedge \alpha \notin \Phi' \implies (\Phi', \alpha) \vdash (\sigma, \alpha\colon = \alpha)\colon (\Phi, \alpha) \tag{3.6}$$

Since $\iota\pi\colon \Phi', \alpha \triangleright \Phi'$ so $\Phi', \alpha \vdash \sigma\colon \Phi$ and $\Phi', \alpha\alpha$

3.3 Term-Environment Weakenings

Type environment weakenings are inductively defined with respect to an effect environment.

$$(\text{T-Id})\frac{\Phi \vdash \Gamma\ \ \mathtt{Ok}}{\Phi \vdash \iota\colon \Gamma \triangleright \Gamma} \qquad (\text{T-Project})\frac{\Phi \vdash \omega\colon \Gamma' \triangleright \Gamma \qquad \Phi \vdash A\colon \mathtt{Type}}{\Phi \vdash \omega\pi\colon \Gamma, x : A \triangleright \Gamma}(\text{if } x \notin \mathtt{dom}(\Gamma'))$$

$$(\text{T-Extend})\frac{\Phi \vdash \omega\colon \Gamma' \triangleright \Gamma \qquad A {\leq\colon} B}{\Phi \vdash \omega\times\colon \Gamma', x : A \triangleright \Gamma, x : B}(\text{if } x \notin \mathtt{dom}(\Gamma'))$$

3.4 Term-Environment Substitutions

3.4.1 Snoc Lists

Term-Environment substitutions may be represented as a snoc-list of variable-term pairs.

$$\sigma\colon\colon = \diamond \mid \sigma, x\colon = v$$

3.4.2 Wellformedness

The relation instance $\Phi' \vdash \sigma \colon \Phi$ means that σ is a substitution from Φ' to Φ. It is defined inductively using the following rules.

$$\text{(T-Nil)}\frac{\Phi' \ \ \mathtt{Ok}}{\Phi' \vdash \diamond \colon \diamond} \qquad \text{(T-Extend)}\frac{\Phi' \vdash \sigma \colon \Phi \qquad \Phi' \epsilon}{\Phi' \vdash \sigma, \alpha \colon = \epsilon \colon (\Phi, \alpha)}(\text{if } \alpha \notin \Phi)$$

3.4.3 Action on Terms

We define the action of applying a term substitution σ as

$$v[\sigma]$$

$$\begin{aligned}
x[\diamond] &= x \\
x[\sigma, x \colon = v] &= v \\
x[\sigma, x' \colon = v'] &= x[\sigma] \quad \text{If } x \neq x' \\
\mathtt{k}^{A}[\sigma] &= \mathtt{k}^{A} \\
(\lambda x \colon A.v\ )[\sigma] &= \lambda x \colon A.(v[\sigma]) \quad \text{If } x \# \sigma \\
(\mathtt{if}_{A}\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2\ )[\sigma] &= \mathtt{if}_{A}\ v[\sigma]\ \mathtt{then}\ v_1[\sigma]\ \mathtt{else}\ v_2[\sigma] \\
(v_1\ v_2)[\sigma] &= (v_1[\sigma])\ v_2[\sigma] \\
(\mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2\ ) &= \mathtt{do}\ x \leftarrow (v_1[\sigma])\ \mathtt{in}\ (v_2[\sigma]) \quad \text{If } x \# \sigma \\
(\Lambda \alpha.v)[\sigma] &= \Lambda \alpha.(v[\sigma]) \\
(v\ \epsilon)[\sigma] &= (v[\sigma])\ \epsilon
\end{aligned}$$

3.4.4 Properties

Property 3.4.1 (Wellformedness)**.** *If $\Phi \mid \Gamma' \vdash \sigma \colon \Gamma$ then $\Phi \vdash \Gamma$ $\mathtt{Ok}$ and $\Phi \vdash \Gamma'$ $\mathtt{Ok}$. Since $\Phi \vdash \Gamma'$ $\mathtt{Ok}$ holds by the Nil axiom. $\Phi \vdash \Gamma$ $\mathtt{Ok}$ holds by induction on the wellformedness relation.*

Property 3.4.2 (Weakening)**.** *If $\Phi \mid \Gamma' \vdash \sigma \colon \Gamma$ then $\omega \colon \Gamma'' \triangleright \Gamma'$ implies $\Phi \mid \Gamma'' \vdash \sigma \colon \Gamma$. By induction over wellformedness relation. For each $x \colon = v$ in σ, $\Phi \mid \Gamma'' \vdash v \colon A$ holds if $\Phi \mid \Gamma' \vdash v \colon A$ holds.*

Property 3.4.3 (Extension)**.** *If $\Phi \mid \Gamma' \vdash \sigma \colon \Gamma$ then $x \notin (\mathit{dom}(\Gamma) \cup \mathit{dom}(\Gamma''))$ implies $\Phi \mid (\Gamma', x : A) \vdash (\sigma, x \colon = x) \colon (\Gamma, x \colon A)$. Since $\iota\pi \colon \Gamma', x : A \triangleright \Gamma'$, so by property* **??***,*

$$\Phi \mid \Gamma', x : A \vdash \sigma \colon \Gamma$$

In addition, $\Phi \mid \Gamma', x : A \vdash x \colon A$ trivially, so by the rule (T-Extend), wellformedness holds for

$$\Phi \mid (\Gamma', x : A) \vdash (\sigma, x \colon = v) \colon (\Gamma, x \colon A) \tag{3.7}$$

Chapter 4

Denotations

4.1 Effects

For each instance of the wellformedness relation on effects, we define a morphism $[\![\Phi \vdash \epsilon\colon \texttt{Effect}]\!] : \mathbb{C}(I, U)$

- $[\![\Phi \vdash e\colon \texttt{Effect}]\!] = [\![\epsilon]\!] \circ \langle\rangle_I :\to U$
- $[\![\Phi, \alpha \vdash \alpha\colon \texttt{Effect}]\!] = \pi_2 : I \times U \to U$
- $[\![\Phi, \beta \vdash \alpha\colon \texttt{Effect}]\!] = [\![\Phi \vdash \alpha\colon \texttt{Effect}]\!] \circ \pi_1 : I \times U \to U$
- $[\![\Phi \vdash \epsilon_1 \cdot \epsilon_2\colon \texttt{Effect}]\!] = \texttt{Mul}_I([\![\Phi \vdash \epsilon_2\colon \texttt{Effect}]\!], [\![\Phi \vdash \epsilon_1\colon \texttt{Effect}]\!]) : I \to U$

4.2 Types

For each instance of the wellformedness relation on types, we derive an object $[\![\Phi \vdash A\colon \texttt{Type}]\!] \in \texttt{obj}\ \mathbb{C}(I)$.

Since the fibre category $\mathbb{C}(I)$ is S-Closed, it has objects for all ground types, a terminal object, graded monad T, exponentials, products, and co-product over $\texttt{1} + \texttt{1}$.

- $[\![\Phi \vdash \texttt{Unit}\colon \texttt{Type}]\!] = \texttt{1}$
- $[\![\Phi \vdash \texttt{Bool}\colon \texttt{Type}]\!] = \texttt{1} + \texttt{1}$
- $[\![\Phi \vdash \gamma\colon \texttt{Type}]\!] = [\![\gamma]\!]$
- $[\![\Phi \vdash A \to B\colon \texttt{Type}]\!] = ([\![\Phi \vdash B\colon \texttt{Type}]\!])^{([\![\Phi \vdash A:\texttt{Type}]\!])}$
- $[\![\Phi \vdash \texttt{M}_\epsilon A\colon \texttt{Type}]\!] = T_{[\![\Phi \vdash \epsilon:\texttt{Effect}]\!]}[\![\Phi \vdash A\colon \texttt{Type}]\!]$
- $[\![\Phi \vdash \forall\alpha.A\colon \texttt{Type}]\!] = \forall_I([\![\Phi, \alpha \vdash A\colon \texttt{Type}]\!])$

4.3 Effect Substitution

For each effect-environment substitution wellformedness-relation, define a denotation morphism, $[\![\Phi' \vdash \sigma\colon \Phi]\!] : \mathbb{C}(I', I)$

- $[\![\Phi' \vdash \diamond\colon \diamond]\!] = \langle\rangle_I : \mathbb{C}(I', \texttt{1})$
- $[\![\Phi' \vdash (\sigma, \alpha := \epsilon)\colon \Phi, \alpha]\!] = \langle [\![\Phi' \vdash \sigma\colon \Phi]\!], [\![\Phi \vdash \epsilon\colon \texttt{Effect}]\!] \rangle : \mathbb{C}(I', I \times U)$

4.4 Effect Weakening

For each instance of the effect-environment weakening relation, define a denotation morphism: $[\![\omega\colon \Phi' \triangleright P]\!] : \mathbb{C}(I', I)$

- $[\![\iota\colon \Phi \triangleright \Phi]\!] = \mathtt{Id}_I : I \to I$
- $[\![w\pi\colon \Phi', \alpha \triangleright \Phi]\!] = [\![\omega\colon \Phi' \triangleright \Phi]\!] \circ \pi_1 : I' \times U \to I$
- $[\![w\times\colon \Phi', \alpha \triangleright \Phi, \alpha]\!] = ([\![\omega\colon \Phi' \triangleright \Phi]\!] \times \mathtt{Id}_U) : I' \times U \to I \times U$

4.5 Subtyping

For each instance of the subtyping relation with respect to an effect environment, there exists a denotation, $[\![A {\leq:}_\Phi B]\!] : \mathbb{C}(I)(A, B)$.

- $[\![\gamma_1 {\leq:}_\Phi \gamma_2]\!] = [\![\gamma_1 {\leq:}_\gamma \gamma_2]\!] : \mathbb{C}(I)(\gamma_1, \gamma_2)$
- $[\![A \to B {\leq:}_\Phi A' \to B']\!] = [\![B {\leq:}_\Phi B']\!]^{A'} \circ B^{[\![A' {\leq:}_\Phi A]\!]}$
- $[\![\mathtt{M}_{\epsilon_1} A {\leq:}_\Phi \mathtt{M}_{\epsilon_2} B]\!] = [\![\epsilon_1 \leq_\Phi \epsilon_2]\!] \circ T_{\epsilon_1}[\![A {\leq:}_\Phi B]\!]$
- $[\![\forall \alpha. A {\leq:}_\Phi \forall \alpha. B]\!] = \forall_I [\![A {\leq:}_{\Phi,\alpha} B]\!]$

4.6 Term-Environments

For each instance of the well formed relation on type environments, define an object $[\![\Phi \vdash \Gamma\ \mathtt{Ok}]\!] \in \mathtt{obj}\ \mathbb{C}(I)$.

- $[\![\Phi \vdash \diamond\ \mathtt{Ok}]\!] = 1 : \mathbb{C}(I)$
- $[\![\Phi \vdash \Gamma, x\colon A\ \ \mathtt{Ok}]\!] = ([\![\Phi \vdash \Gamma\ \ \mathtt{Ok}]\!] \times [\![\Phi \vdash A\colon \mathtt{Type}]\!])$

4.7 Terms

For each instance of the typing relation, define a denotation morphism: $[\![\Phi \mid \Gamma \vdash v\colon A]\!] : \mathbb{C}(I)(\Gamma_I, A_I)$. Writing Γ_I and A_I for $[\![\Phi \vdash \Gamma\ \ \mathtt{Ok}]\!]$ and $[\![\Phi \vdash A\colon \mathtt{Type}]\!]$.

For each ground constant, $\mathtt{k}^A$, there exists $c : 1 \to A_I$ in $\mathbb{C}(I)$.

- (Unit) $\dfrac{\Phi \vdash \Gamma\ \ \mathtt{Ok}}{[\![\Phi \mid \Gamma \vdash ()\colon \mathtt{Unit}]\!] = \langle\rangle_\Gamma : \Gamma_I \to 1}$
- (Const) $\dfrac{\Phi \vdash \Gamma\ \ \mathtt{Ok}}{[\![\Phi \mid \Gamma \vdash \mathtt{k}^A\colon A]\!] = [\![\mathtt{k}^A]\!] \circ \langle\rangle_\Gamma : \Gamma \to [\![A]\!]}$
- (True) $\dfrac{\Phi \vdash \Gamma\ \ \mathtt{Ok}}{[\![\Phi \mid \Gamma \vdash \mathtt{true}\colon \mathtt{Bool}]\!] = \mathtt{inl} \circ \langle\rangle_\Gamma : \Gamma \to [\![\mathtt{Bool}]\!] = 1 + 1}$
- (False) $\dfrac{\Phi \vdash \Gamma\ \ \mathtt{Ok}}{[\![\Phi \mid \Gamma \vdash \mathtt{false}\colon \mathtt{Bool}]\!] = \mathtt{inr} \circ \langle\rangle_\Gamma : \Gamma \to [\![\mathtt{Bool}]\!] = 1 + 1}$

- (Var) $\dfrac{\Phi \vdash \Gamma \ \texttt{Ok}}{[\![\Phi \mid \Gamma, x{:}\, A \vdash x{:}\, A]\!] = \pi_2 : \Gamma \times A \to A}$

- (Weaken) $\dfrac{f = [\![\Phi \mid \Gamma \vdash x{:}\, A]\!] : \Gamma \to A}{[\![\Phi \mid \Gamma, y{:}\, B \vdash x{:}\, A]\!] = f \circ \pi_1 : \Gamma \times B \to A}$

- (Fn) $\dfrac{f = [\![\Phi \mid \Gamma, x{:}\, A \vdash v{:}\, B]\!] : \Gamma \times A \to B}{[\![\Phi \mid \Gamma \vdash \lambda x{:}\, A.v : A \to B]\!] = \texttt{cur}(f) : \Gamma \to (B)^A}$

- (Subtype) $\dfrac{f = [\![\Phi \mid \Gamma \vdash v{:}\, A]\!] : \Gamma \to A \qquad g = [\![A \leq :_\Phi B]\!]}{[\![\Phi \mid \Gamma \vdash v{:}\, B]\!] = g \circ f : \Gamma \to B}$

- (Return) $\dfrac{f = [\![\Phi \mid \Gamma \vdash v{:}\, A]\!]}{[\![\Phi \mid \Gamma \vdash \texttt{return}\ v : \texttt{M}_{\mathbf{1}} A]\!] = \eta_A \circ f}$

- (If) $\dfrac{f = [\![\Phi \mid \Gamma \vdash v{:}\texttt{Bool}]\!] : \Gamma \to \mathtt{1} + \mathtt{1} \qquad g = [\![\Phi \mid \Gamma \vdash v_1{:}\texttt{M}_\epsilon A]\!] \qquad h = [\![\Phi \mid \Gamma \vdash v_2{:}\texttt{M}_\epsilon A]\!]}{[\![\Phi \mid \Gamma \vdash \texttt{if}_{\epsilon,A}\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2 : \texttt{M}_\epsilon A]\!] = \texttt{app} \circ (([\texttt{cur}(g \circ \pi_2), \texttt{cur}(h \circ \pi_2)] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma : \Gamma \to T_\epsilon A}$

- (Bind) $\dfrac{f = [\![\Phi \mid \Gamma \vdash v_1{:}\texttt{M}_{\epsilon_1} A : \Gamma \to T_{\epsilon_1} A]\!] \qquad g = [\![\Phi \mid \Gamma, x{:}\, A \vdash v_2{:}\texttt{M}_{\epsilon_2} B]\!] : \Gamma \times A \to T_{\epsilon_2} B}{[\![\Phi \mid \Gamma \vdash \texttt{do}\ x \leftarrow v_1\ \texttt{in}\ v_2 : \texttt{M}_{\epsilon_1 \cdot \epsilon_2} B]\!] = \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1} g \circ \texttt{t}_{\Gamma, A, \epsilon_1} \circ \langle \texttt{Id}_\Gamma, f \rangle : \Gamma \to T_{\epsilon_1 \cdot \epsilon_2} B}$

- (Apply) $\dfrac{f = [\![\Phi \mid \Gamma \vdash v_1{:}\, A \to B]\!] : \Gamma \to (B)^A \qquad g = [\![\Phi \mid \Gamma \vdash v_2{:}\, A]\!] : \Gamma \to A}{[\![\Phi \mid \Gamma \vdash v_1\ v_2{:}\, B]\!] = \texttt{app} \circ \langle f, g \rangle : \Gamma \to B}$

- (Effect-Gen) $\dfrac{f = [\![\Phi, \alpha \mid \Gamma \vdash v{:}\, A]\!] : \mathbb{C}(I \times U, W)(\Gamma, A)}{[\![\Phi \mid \Gamma \vdash \Lambda\alpha.A{:}\, \forall\epsilon.A]\!] = \overline{f} : \mathbb{C}(I)(\Gamma, \forall_I(A))}$

- (Effect-Spec) $\dfrac{g = [\![\Phi \mid \Gamma \vdash v{:}\forall\alpha.A]\!] : \mathbb{C}(I)(\Gamma, \forall_I(A)) \qquad h = [\![\Phi \vdash \epsilon{:}\,\texttt{Effect}]\!] : \mathbb{C}(I, U)}{[\![\Phi \mid \Gamma \vdash v\ \epsilon{:}\, A[\epsilon/\alpha]]\!] = \langle \texttt{Id}_I, h \rangle^* (\epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] : \texttt{Type}]\!]}) \circ g : \mathbb{C}(I)(\Gamma, A[\epsilon/\alpha])}$

4.8 Term Weakening

For each instance of the term-environment weakening relation, define a morphism $[\![\Phi \vdash \omega{:}\, \Gamma' \triangleright \Gamma]\!] : \Gamma' \to \Gamma \in \mathbb{C}(I)$

- $[\![\Phi \vdash \iota{:}\, \Gamma \triangleright \Gamma]\!] = \texttt{Id}_\Gamma : \Gamma \to \Gamma \in \mathbb{C}(I)$
- $[\![\Phi \vdash \omega\pi{:}\, \Gamma', ax \triangleright \Gamma]\!] = [\![\Phi \vdash \omega{:}\, \Gamma' \triangleright \Gamma]\!] \circ \pi_1 : \Gamma' \times A \to \Gamma$
- $[\![\Phi \vdash \omega\times{:}\, \Gamma', x : A \triangleright \Gamma, x : B]\!] = [\![\Phi \vdash \omega{:}\, \Gamma' \triangleright \Gamma]\!] \times [\![A \leq :_\Phi B]\!] : \Gamma' \times A \to \Gamma \times B$

4.9 Term Substitutions

For each instance of the term-environment substitution relation, define a denotation morphism: $[\![\Phi \mid \Gamma' \vdash \sigma{:}\, \Gamma]\!] : \Gamma' \to \Gamma \in \mathbb{C}(I)$

- $[\![\Phi \mid \Gamma' \vdash \diamond{:}\, \diamond]\!] = \langle\rangle_{\Gamma'} : \Gamma' \to \mathtt{1}$
- $[\![\Phi \mid \Gamma' \vdash (\sigma, x{:}= v){:}\, \Gamma, x{:}\, A]\!] = \langle [\![\Phi \mid \Gamma' \vdash \Gamma{:}\,]\!], [\![\Phi \mid \Gamma' \vdash v{:}\, A]\!] \rangle : \Gamma' \to \Gamma \times \mathtt{1}$

Chapter 5

Effect Substitution Theorem

In this section, we state and prove a theorem that the action of a simultaneous effect-variable substitution upon a structure in the language has a consistent effect upon the denotation of the language. More formally, for the denotation morphism Δ of some relation, the denotation of the substituted relation, $\Delta' = \sigma^*(\Delta)$.

5.1 Effects

Theorem 5.1.1 (Effect Substitution Preserves Effect Wellformedness). *If* $\Phi\epsilon$ *and* $\Phi' \vdash \iota\colon \Phi$ *then* $\Phi'\sigma(\epsilon)$

Proof:

Case E-Ground: $\sigma(e) = e$, so $\Phi'\sigma(\epsilon)$ holds.

Case E-Compose: By inversion, $\Phi\epsilon_1$ and $\Phi\epsilon_2$ so $\Phi'\sigma(\epsilon_1)$ and $\Phi'\sigma(\epsilon_2)$ by induction and hence $\Phi'\sigma(\epsilon_1 \cdot \epsilon_2)$

Case E-Var: By inversion, $\Phi = \Phi'', \alpha$ and Φ'', α `Ok`. Hence by case splitting on ι, we see that $\sigma = \sigma', \alpha\colon = \epsilon$.

So by inversion, $\Phi\epsilon$ so $\Phi'\sigma(\alpha) = \epsilon$

Case E-Weaken: By inversion, $\Phi = \Phi'', \beta$ and $\Phi''\alpha$, so $\sigma = \sigma'\beta\colon = \epsilon$.

So $\Phi' \vdash \sigma'\colon \Phi''$.

hence by induction, $\Phi'\sigma'(a)$, so $\Phi'\sigma(\alpha)$ since $\alpha \neq \beta$)

Theorem 5.1.2 (Effect Substitution Preserves the Subeffect Relation). *If* $\Phi' \vdash \sigma\colon \Phi$ *and* $\epsilon_1 \leq_\Phi \epsilon_2$, *then* $\epsilon_1[\sigma] \leq_{\Phi'} \epsilon_2[\sigma]$.

Proof: For any ground substitution σ' of Φ', then $\sigma\sigma'$ (the substitution σ' applied after σ) is also a ground substitution.

So $\epsilon_1[\sigma][\sigma'] \leq \epsilon_2[\sigma][\sigma']$.

So $\epsilon_1[\sigma] \leq_{\Phi'} \epsilon_2[\sigma]$.

Theorem 5.1.3 (Effect Substitution and Effect Denotation)**.** *If* $\sigma = [\![\Phi' \vdash \sigma : \Phi]\!]$ *then*

$[\![\Phi' \vdash \sigma(\epsilon) : \mathtt{Effect}]\!] = \sigma^* [\![\Phi \vdash \epsilon : \mathtt{Effect}]\!] = [\![\Phi \vdash \epsilon : \mathtt{Effect}]\!] \circ \sigma$.

Proof: By induction on the derivation on $[\![\Phi \vdash \epsilon : \mathtt{Effect}]\!]$

Case E-Ground:

$$\begin{aligned}[\![\Phi \vdash e : \mathtt{Effect}]\!] \circ \sigma &= [\![e]\!] \circ \langle\rangle_I \circ \sigma \\ &= [\![e]\!] \circ \langle\rangle_{I'} \\ &= [\![\Phi' \vdash e : \mathtt{Type}]\!]\end{aligned}$$

Case E-Var:

$$\begin{aligned}[\![\Phi, \alpha \vdash \alpha : \mathtt{Effect}]\!] \circ \sigma' &= \pi_2 \circ \langle \sigma, [\![\Phi' \vdash \epsilon : \mathtt{Effect}]\!]\rangle && \text{By inversion, } \sigma' = (\sigma, \alpha := \epsilon) \\ &= [\![\Phi' \vdash \epsilon : \mathtt{Effect}]\!] \\ &= [\![\Phi' \vdash \sigma'(\alpha) : \mathtt{Effect}]\!]\end{aligned}$$

Case E-Weaken:

$$\begin{aligned}[\![\Phi, \beta \vdash \alpha : \mathtt{Type}]\!] \circ \sigma' &= [\![\Phi \vdash \alpha : \mathtt{Type}]\!] \circ \pi_1 \circ \langle \sigma, [\![\Phi' \vdash \epsilon : \mathtt{Effect}]\!]\rangle && \text{By inversion, } \sigma' = (\sigma, \beta := \epsilon) \\ &= [\![\Phi \vdash \alpha : \mathtt{Type}]\!] \circ \sigma \\ &= [\![\Phi' \vdash \sigma(\alpha) : \mathtt{Type}]\!] \\ &= [\![\Phi' \vdash \sigma'(\alpha) : \mathtt{Type}]\!]\end{aligned}$$

Case E-Compose:

$$\begin{aligned}[\![\Phi \vdash \epsilon_1 \cdot \epsilon_2 : \mathtt{Type}]\!] \circ \sigma &= \mathtt{Mul}_I([\![\Phi \vdash \epsilon_1 : \mathtt{Effect}]\!], [\![\Phi \vdash \epsilon_2 : \mathtt{Effect}]\!]) \circ \sigma \\ &= \mathtt{Mul}_{I'}([\![\Phi \vdash \epsilon_1 : \mathtt{Effect}]\!] \circ \sigma, [\![\Phi \vdash \epsilon_2 : \mathtt{Effect}]\!] \circ \sigma) && \text{By Naturality} \\ &= \mathtt{Mul}_{I'}([\![\Phi' \vdash \sigma(\epsilon_1) : \mathtt{Effect}]\!], [\![\Phi \vdash \sigma(\epsilon_2) : \mathtt{Effect}]\!]) \\ &= [\![\Phi' \vdash \sigma(\epsilon_1) \cdot \sigma(\epsilon_2) : \mathtt{Effect}]\!] \\ &= [\![\Phi' \vdash \sigma(\epsilon_1 \cdot \epsilon_2) : \mathtt{Effect}]\!]\end{aligned}$$

5.2 Types

Theorem 5.2.1 (Effect Substitution Preserves Type Wellformedness). *If* $\Phi' \vdash \sigma \colon \Phi$ *and* ΦA *then* $\Phi' A[\sigma]$

Proof:

Case T-Ground: Φ' $\texttt{Ok}$ so $\Phi'\gamma$ and $\gamma[\sigma] = \gamma$.

Hence $\Phi'\gamma[\sigma]$.

Case T-Fn: By inversion, ΦA and ΦB.

So by induction, $\Phi' A[\sigma]$ and $\Phi' B[\sigma]$.

So

$$\Phi'(A[\sigma]) \to (B[\sigma]) \tag{5.1}$$

So

$$\Phi'(A \to B)[\sigma] \tag{5.2}$$

Case T-Effect: By inversion, $\Phi\epsilon$ and ΦA so by induction and substitution of effect preserving effect-wellformedness,

$\Phi'\sigma(\epsilon)$ and $\Phi' A[\sigma]$ so $\Phi \texttt{M}_{\sigma(\epsilon)} A[\sigma]$ so $\Phi'(\texttt{M}_\epsilon A)[\sigma]$

Case T-Quantification: By inversion, $\Phi, \alpha A$. So by picking $\alpha \notin \Phi \wedge \alpha \notin \Phi'$ using α-equivalence, we have $(\Phi', \alpha) \vdash (\sigma\alpha \colon= \alpha) \colon (\Phi, \alpha)$.

So by induction $(\Phi, \alpha) A[\sigma, \alpha \colon= \alpha]$

So $(\Phi', \alpha) A[\sigma]$

So $\Phi'(\forall \alpha . A)[\sigma]$

Theorem 5.2.2 (Effect Substitution and Type Denotations). *If* $\sigma = [\![\Phi' \vdash \sigma \colon \Phi]\!]$ *then* $[\![\Phi' \vdash A[\sigma] \colon \mathit{Type}]\!] = \sigma^* [\![\Phi \vdash A \colon \mathit{Type}]\!]$.

Proof: By induction on the derivation on $[\![\Phi \vdash A \colon \texttt{Type}]\!]$. Making use of the S-Closure of the re-indexing functor.

Case T-Ground:

$$\begin{aligned} \sigma^* [\![\Phi \vdash \gamma \colon \texttt{Type}]\!] &= \sigma^* [\![\gamma]\!] \\ &= [\![\gamma]\!] \quad \text{By S-Closure} \\ &= [\![\Phi' \vdash \gamma[\sigma] \colon \texttt{Type}]\!] \end{aligned}$$

Case T-Effect:

$$\begin{aligned}\sigma^*[\![\Phi \vdash \mathtt{M}_\epsilon A\colon \mathtt{Type}]\!] &= \sigma^*(T_{[\![\Phi\vdash\epsilon:\mathtt{Effect}]\!]}[\![\Phi \vdash A\colon \mathtt{Type}]\!])\\ &= T_{\sigma^*([\![\Phi\vdash\epsilon:\mathtt{Effect}]\!])}\sigma^*([\![\Phi \vdash A\colon \mathtt{Type}]\!])\\ &= [\![\Phi' \vdash (\mathtt{M}_\epsilon A)[\sigma]\colon \mathtt{Type}]\!]\end{aligned}$$

Case T-Quantification:

$$\begin{aligned}\sigma^*[\![\Phi \vdash \forall\alpha.A\colon \mathtt{Type}]\!] &= \sigma^*(\forall_I([\![\Phi,\alpha \vdash A\colon \mathtt{Type}]\!]))\\ &= \forall_I((\sigma\times\mathtt{Id}_U)^*[\![\Phi,\alpha \vdash A\colon \mathtt{Type}]\!]) \quad \text{By Beck-Chevalley}\\ &= \forall_I([\![\Phi',\alpha \vdash A[\sigma,\alpha\colon=\alpha]\colon \mathtt{Type}]\!])\\ &= \forall_I([\![\Phi',\alpha \vdash A[\sigma]\colon \mathtt{Type}]\!])\\ &= [\![\Phi' \vdash \forall\alpha.A[\sigma]\colon \mathtt{Type}]\!]\\ &= [\![\Phi' \vdash (\forall\alpha.A)[\sigma]\colon \mathtt{Type}]\!]\end{aligned}$$

Case T-Fn:

$$\begin{aligned}\sigma^*[\![\Phi \vdash A\to B\colon \mathtt{Type}]\!] &= \sigma^*([\![\Phi \vdash B\colon \mathtt{Type}]\!]^{[\![\Phi\vdash A:\mathtt{Type}]\!]})\\ &= \sigma^*([\![\Phi \vdash B\colon \mathtt{Type}]\!])^{\sigma^*([\![\Phi\vdash A:\mathtt{Type}]\!])}\\ &= [\![\Phi' \vdash B[\sigma]\colon \mathtt{Type}]\!]^{[\![\Phi'\vdash A[\sigma]:\mathtt{Type}]\!]}\\ &= [\![\Phi' \vdash (A[\sigma])\to(B[\sigma])\colon \mathtt{Type}]\!]\\ &= [\![\Phi' \vdash (A\to B)[\sigma]\colon \mathtt{Type}]\!]\end{aligned}$$

5.3 Subtyping

Theorem 5.3.1 (Effect Substitution Preserves the Subtyping Relation)**.** *If $\Phi' \vdash \sigma\colon\Phi$ and $A{\leq:}_\Phi B$ then $A[\sigma]{\leq:}_{\Phi'}B[\sigma]$*

Proof: By induction on the subtyping relation

Case S-Ground: By inversion, $A{\leq:}_\gamma B$, so A, B are ground types. Hence $A[\sigma]=A$ and $B[\sigma]=B$. So $A[\sigma]{\leq:}_{\Phi'}B[\sigma]$

Case S-Fn: By inversion, $A'{\leq:}_\Phi A$ and $B{\leq:}_\Phi B'$.

So by induction, $A'[\sigma]{\leq:}_{\Phi'}A[\sigma]$ and $B[\sigma]{\leq:}_{\Phi'}B'[\sigma]$.

So $(A[\sigma])\to(B[\sigma]){\leq:}_{\Phi'}(A'[\sigma])\to(B'[\sigma])$

So $(A\to B)[\sigma]{\leq:}_{\Phi'}(A'\to B')[\sigma]$

Case S-Effect: By inversion, $A \leq:_{\Phi} B$, $\epsilon_1 \leq_{\Phi} \epsilon_2$.

So by induction and substitution preserving the subeffect relation,

$A[\sigma] \leq:_{\Phi'} B[\sigma]$ and $\sigma(\epsilon_1) \leq_{\Phi'} \sigma(\epsilon_2)$

So $\mathtt{M}_{\sigma(\epsilon_1)}(A[\sigma]) \leq:_{\Phi'} \mathtt{M}_{\sigma(\epsilon_2)}(B[\sigma])$

So $(\mathtt{M}_{\epsilon_1} A)[\sigma] \leq:_{\Phi'} (\mathtt{M}_{\epsilon_2} B)[\sigma]$

Case S-Quantification: By inversion, $A \leq:_{\Phi,\alpha} B$ and Φ, α $\mathtt{Ok}$. Picking $\alpha \notin \Phi'$ by α equivalence, and by the extension lemma **??**, $(\Phi, \alpha) \vdash (\sigma, \alpha := \alpha) : (\Phi, \alpha)$. Hence, by induction $A[\sigma, \alpha := \alpha] \leq:_{\Phi',\alpha} B[\sigma, \alpha := \alpha]$, so $\forall \alpha. A \leq:_{\Phi'} \forall \alpha. B$.

□

Theorem 5.3.2 (Effect Substitution and Subtyping Denotations). *If* $\sigma = [\![\Phi' \vdash \sigma : \Phi]\!]$ *then* $[\![A[\sigma] \leq:_{\Phi'} B[\sigma]]\!] = \sigma^* [\![A \leq:_{\Phi} B]\!] : \mathbb{C}(I')(A, B)$.

Proof: By induction on the derivation on $[\![A \leq:_{\Phi} B]\!]$. Using S-preserving property of σ^*

Case S-Ground:

$$\sigma^*(\gamma_1 \leq:_{\gamma} \gamma_2) = (\gamma_1 \leq:_{\gamma} \gamma_2)$$

Since σ^* is s-closed.

Case S-Effect:

$$\begin{aligned}
\sigma^* [\![\mathtt{M}_{\epsilon_1} A \leq:_{\Phi} \mathtt{M}_{\epsilon_2} B]\!] &= \sigma^*([\![\epsilon_1 \leq_{\Phi} \epsilon_2]\!]) \circ \sigma^*(T_{\epsilon_1}([\![A \leq:_{\Phi} B]\!])) \\
&= [\![\sigma(\epsilon_1) \leq_{\Phi'} \sigma(\epsilon_2)]\!] \circ T_{\sigma(\epsilon_1)} [\![A[\sigma] \leq:_{\Phi'} B[\sigma]]\!] \quad \text{By S-Closure} \\
&= [\![\mathtt{M}_{\sigma(\epsilon_1)} A[\sigma] \leq:_{\Phi'} \mathtt{M}_{\sigma(\epsilon_2)} B[\sigma]]\!] \\
&= [\![(\mathtt{M}_{\epsilon_1} A)[\sigma] \leq:_{\Phi'} \mathtt{M}_{\epsilon_2} B[\sigma]]\!]
\end{aligned}$$

Case S-Quantification:

$$\begin{aligned}
\sigma^* [\![\forall \alpha. A \leq:_{\Phi} \forall \alpha. B]\!] &= \sigma^*(\forall_I([\![A \leq:_{\Phi,\alpha} B]\!])) \\
&= \forall_{I'}((\sigma \times \mathtt{Id}_U)^*([\![A \leq:_{\Phi,\alpha} B]\!])) \\
&= \forall_{I'}([\![A[\sigma, \alpha := \alpha] \leq:_{\Phi',\alpha} B[\sigma, \alpha := \alpha]]\!]) \\
&= [\![(\forall \alpha. A)[\sigma] \leq:_{\Phi'} (\forall \alpha. B)[\sigma]]\!]
\end{aligned}$$

Case S-Fn:

$$
\begin{aligned}
&\sigma^*[\![(A \to B) \leq:_\Phi A' \to B']\!] \\
&\quad = \sigma^*([\![B \leq:_\Phi B']\!]^{A'} \circ B^{[\![A' \leq:_\Phi A]\!]}) \\
&\quad = \sigma^*(\texttt{cur}([\![B \leq:_\Phi B']\!] \circ \texttt{app})) \circ \sigma^*(\texttt{cur}(\texttt{app} \circ (\texttt{Id}_B \times [\![A' \leq:_\Phi A]\!]))) \\
&\quad = \texttt{cur}(\sigma^*([\![B \leq:_\Phi B']\!]) \circ \texttt{app}) \circ \texttt{cur}(\texttt{app} \circ (\texttt{Id}_B \times \sigma^*([\![A' \leq:_\Phi A]\!]))) \\
&\quad = \texttt{cur}([\![B[\sigma] \leq:_{\Phi'} B'[\sigma]]\!] \circ \texttt{app}) \circ \texttt{cur}(\texttt{app} \circ (\texttt{Id}_{B[\sigma]} \times [\![A'[\sigma] \leq:_{\Phi'} A[\sigma]]\!])) \\
&\quad = [\![(A[\sigma]) \to (B[\sigma]) \leq:_{\Phi'} (A'[\sigma]) \to (B'[\sigma])]\!] \\
&\quad = [\![(A \to B)[\sigma] \leq:_{\Phi'} (A' \to B')[\sigma]]\!]
\end{aligned}
$$

5.4 Term Environments

Theorem 5.4.1 (Effect Substitution Preserves Term-Environment wellformedness)**.** *If* $\Phi \vdash \Gamma$ *Ok and* $\Phi' \vdash \sigma : \Phi$ *then* $\Phi' \vdash \Gamma[\sigma]$ *Ok*

Proof:

Case Env-Nil: Φ $\texttt{Ok} \implies \Phi'$ $\texttt{Ok}$ so $\Phi' \vdash \diamond$ $\texttt{Ok}$ and $\diamond[\sigma] = \diamond$

Case Env-Extend: By inversion, $\Phi \vdash \Gamma$ $\texttt{Ok}$ and ΦA.

By induction and substitution preserving wellformedness of types, $\Phi' \vdash \Gamma'[\sigma]$ $\texttt{Ok}$ and $\Phi' A[\sigma]$.

So $\Phi' \vdash (\Gamma'[\sigma], x : A[\sigma])$ $\texttt{Ok}$.

Hence $\Phi' \vdash \Gamma, x \colon A[\sigma]$ $\texttt{Ok}$.

Theorem 5.4.2 (Effect Substitution and Term Environment Denotations)**.** *If* $\sigma = [\![\Phi' \vdash \sigma : \Phi]\!]$ *then* $[\![\Phi' \vdash \Gamma[\sigma]\ \textit{Ok}]\!] = \sigma^*[\![\Phi \vdash \Gamma\ \textit{Ok}]\!] \in \textit{obj}\ \mathbb{C}(I')$.

Proof: By induction on the derivation on $[\![\Phi \vdash \Gamma\ \texttt{Ok}]\!]$. Using the S-Closure of the re-indexing functor.

Case Env-Nil:

$$
\begin{aligned}
\sigma^*[\![\Phi \vdash \diamond\ \texttt{Ok}]\!] &= \sigma^* \texttt{1} \\
&= \texttt{1} \quad \text{By S-preservation} \\
&= [\![\Phi' \vdash \diamond\ \texttt{Ok}]\!] \\
&= [\![\Phi' \vdash \diamond[\sigma]\ \texttt{Ok}]\!]
\end{aligned}
$$

Case Env-Extend:

$$\begin{aligned}
\sigma^*[\![\Phi \vdash \Gamma, x\colon A \;\; \texttt{Ok}]\!] &= \sigma^*([\![\Phi \vdash \Gamma \;\; \texttt{Ok}]\!] \times [\![\Phi \vdash A\colon \texttt{Type}]\!]) \\
&= (\sigma^*[\![\Phi \vdash \Gamma \;\; \texttt{Ok}]\!] \times \sigma^*[\![\Phi \vdash A\colon \texttt{Type}]\!]) \\
&= ([\![\Phi' \vdash \Gamma[\sigma] \;\; \texttt{Ok}]\!] \times [\![\Phi' \vdash A[\sigma]\colon \texttt{Type}]\!]) \\
&= [\![\Phi' \vdash \Gamma[\sigma], x : A[\sigma] \;\; \texttt{Ok}]\!] \\
&= [\![\Phi' \vdash (\Gamma, x\colon A)[\sigma] \;\; \texttt{Ok}]\!]
\end{aligned}$$

5.5 Terms

Theorem 5.5.1 (Effect-Environment Substitution Preserves the Typing Relation)**.** *If* $\Phi' \vdash \sigma\colon \Phi$ *and* $\Phi \mid \Gamma \vdash v\colon A$*, then* $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma]\colon A[\sigma]$

Proof:

Case Const: By inversion, $\Phi \vdash \Gamma \;\; \texttt{Ok}$.

So $\Phi' \vdash \Gamma \;\; \texttt{Ok}$

So $\Phi' \mid \Gamma[\sigma] \vdash \texttt{k}^{A[\sigma]}\colon A[\sigma]$

Case True, False, Unit: The logic is the same for each of these cases, so we look at the case `true` only.

By inversion, $\Phi \vdash \Gamma \;\; \texttt{Ok}$.

So $\Phi' \vdash \Gamma \;\; \texttt{Ok}$

So $\Phi' \mid \Gamma[\sigma] \vdash \texttt{true}\colon \texttt{Bool}$

Since $\texttt{true}[\sigma] = \texttt{true}$ and $\texttt{Bool}[\sigma] = \texttt{Bool}$.

Case Var: By inversion, $\Gamma = \Gamma', x : A$ and $\Phi \vdash \Gamma', x : A \;\; \texttt{Ok}$.

So since substitution preserves wellformedness of type environments, $\Phi' \vdash \Gamma'[\sigma], x : A[\sigma] \;\; \texttt{Ok}$

So $\Phi' \mid \Gamma[\sigma] \vdash x\colon A[\sigma]$

Since $x[\sigma] = x$

Case Weaken: By inversion, $\Gamma = \Gamma', y : B$, ΦB, and $\Phi \mid \Gamma' \vdash x\colon A$. $x \neq y$

By induction and the theorem that effect-environment substitution preserves type wellformedness, we have: $\Phi' \mid \Gamma'[\sigma] \vdash x\colon A[\sigma]$ and $\Phi' B[\sigma]$

So $\Phi' \mid \Gamma[\sigma] \vdash x[\sigma]\colon A[\sigma]$

Since $x[\sigma] = x$, $\Gamma[\sigma] = (\Gamma'[\sigma], y : B[\sigma])$

Case Fn: By inversion, $\Phi \mid \Gamma, x\colon A \vdash v\colon B$.

So, by induction $\Phi' \mid (\Gamma, x\colon A)[\sigma] \vdash v[\sigma]\colon B[\sigma]$.

So, $\Phi \mid \Gamma[\sigma], x : A[\sigma] \vdash v[\sigma]\colon B[\sigma]$.

Hence by the lambda type rule,

$\Phi' \mid \Gamma[\sigma] \vdash \lambda x\colon A[\sigma].v[\sigma] : (A[\sigma]) \to (B[\sigma])$

So

$\Phi' \mid \Gamma[\sigma] \vdash (\lambda x\colon A.v\ )[\sigma]\colon (A \to B)[\sigma])$

Case Apply: By inversion, $\Phi \mid \Gamma \vdash v_1\colon A \to B$, $\Phi \mid \Gamma \vdash V_2\colon A$.

So by induction, $\Phi' \mid \Gamma[\sigma] \vdash v_1[\sigma]\colon (A[\sigma]) \to (B[\sigma])$.

So $\Phi' \mid \Gamma[\sigma] \vdash (v_1[\sigma])\ (v_2[\sigma])\colon B[\sigma]$.

So $\Phi' \mid \Gamma[\sigma] \vdash (v_1\ v_2)[\sigma]\colon (A \to B)[\sigma]$

Case Subtype: By inversion, $\Phi \mid \Gamma \vdash v\colon A$ and $\Phi A {\leq:} B$

So by induction and effect-environment substitution preserving subtyping, $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma]\colon A[\sigma]$ and $\Phi' A[\sigma] {\leq:} B[\sigma]$

So $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma]\colon B[\sigma]$

Case Return: By inversion, $\Phi \mid \Gamma \vdash v\colon A$

So by induction, $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma]\colon A[\sigma]$

So $\Phi' \mid \Gamma[\sigma] \vdash \mathtt{return}\ (v[\sigma]) : \mathtt{M}_{\mathtt{1}}(A[\sigma])$

Hence $\Phi' \mid \Gamma[\sigma] \vdash (\mathtt{return}\ v\ )[\sigma]\colon (\mathtt{M}_{\mathtt{1}} A)[\sigma]$

Case Bind: By inversion, $\Phi \mid \Gamma \vdash v_1\colon \mathtt{M}_{\epsilon_1} A$ and $\Phi \mid \Gamma, x\colon A \vdash v_2\colon \mathtt{M}_{\epsilon_2} B$.

So by induction: $\Phi' \mid \Gamma[\sigma] \vdash v_1[\sigma]\colon \mathtt{M}_{\sigma(\epsilon_1)}(A[\sigma])$, and $\Phi' \mid \Gamma[\sigma], x : A[\sigma] \vdash v_2\colon \mathtt{M}_{\sigma(\epsilon_2)}(B[\sigma])$.

And so $\Phi' \mid \Gamma[\sigma] \vdash \mathtt{do}\ x \leftarrow (v_1[\sigma])\ \mathtt{in}\ (v_2[\sigma]) : \mathtt{M}_{\sigma(\epsilon_1)\cdot(\epsilon_2[\sigma])} B[\sigma]$

Case If: By inversion, $\Phi \mid \Gamma \vdash v\colon \mathtt{Bool}$, $\Phi \mid \Gamma \vdash v_1\colon A$, and $\Phi \mid \Gamma \vdash v_2\colon A$

So by induction $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma]\colon \mathtt{Bool}$, $\Phi' \mid \Gamma[\sigma] \vdash v_1\colon A[\sigma]$, and $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma]\colon \mathtt{Bool}$, $\Phi' \mid \Gamma[\sigma] \vdash v_2\colon A[\sigma]$. (Since $\mathtt{Bool}[\sigma] = \mathtt{Bool}$)

Hence:

$\Phi' \mid \Gamma[\sigma] \vdash \mathtt{if}_{A[\sigma]}\ v[\sigma]\ \mathtt{then}\ v_1[\sigma]\ \mathtt{else}\ v_2[\sigma] : A[\sigma]$

So $\Phi' \mid \Gamma[\sigma] \vdash (\mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2\ )[\sigma]\colon A[\sigma]$

Case Effect-Gen: By inversion, $\Phi, \alpha \mid \Gamma \vdash v\colon A$.

So by the substitution property **??**, pick $\alpha \notin \Phi' \wedge \alpha \notin \Phi$ so we have:

$$(\Phi', \alpha) \vdash (\sigma, \alpha{:=}\, \alpha)\colon (\Phi, \alpha)$$

So by induction, $\Phi', \alpha \mid \Gamma[\sigma, \alpha{:=}\, \alpha] \vdash v[\sigma, \alpha{:=}\, \alpha]\colon A[\sigma, \alpha{:=}\, \alpha]$

So $\Phi', \alpha \mid \Gamma[\sigma] \vdash v[\sigma] \colon A[\sigma]$ since $\alpha \notin \Phi' \wedge \alpha \notin \Phi$.

So $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma] \colon (\forall\alpha.A)[\sigma]$

Case Effect-Spec: By inversion, $\Phi \mid \Gamma \vdash v \colon \forall\alpha.A$, $\Phi\epsilon$.

So by induction and effect-environment substitution preserving wellformedness of effects: $\Phi' \mid \Gamma[\sigma] \vdash v[\sigma] \colon (\forall\alpha.A)[\sigma]$ and $\Phi'\sigma(\epsilon)$

So $\Phi' \mid \Gamma[\sigma] \vdash (v[\sigma])\ (\sigma(\epsilon)) \colon A[\sigma][\sigma(\epsilon)/\alpha]$.

Since $\alpha\#\sigma$, we can commute the applications of substitution.

So, $\Phi' \mid \Gamma[\sigma] \vdash (v\ \epsilon)[\sigma] \colon A[\epsilon/\alpha][\sigma]$

Theorem 5.5.2 (Effect Substitution and Term Denotations)**.** *If*

$$\begin{aligned}\sigma &= [\![\Phi' \vdash \sigma \colon \Phi]\!]\\ \Delta &= [\![\Phi \mid \Gamma \vdash v \colon A]\!]\\ \Delta' &= [\![\Phi' \mid \Gamma[\sigma] \vdash v[\sigma] \colon A[\sigma]]\!]\end{aligned}$$

Then

$$\Delta' = \sigma^*(\Delta) \tag{5.3}$$

Proof: By induction over the derivation of Δ. Using the S-Closure of σ^*. We use Γ_I to indicate $[\![\Phi \vdash \Gamma\ \mathtt{Ok}]\!]$, an A_I to indicate $[\![\Phi \vdash A \colon \mathtt{Type}]\!]$

Case Unit:

$$\Delta = \langle\rangle_{\Gamma_I} \tag{5.4}$$

So

$$\sigma^*(\Delta) = \langle\rangle_{\Gamma_I[\sigma]} = \Delta' \tag{5.5}$$

Case True, False: Giving the case for true as false is the same but using `inr`

$$\Delta = \mathtt{inl} \circ \langle\rangle_{\Gamma_I} \tag{5.6}$$

So

$$\sigma^*(\Delta) = \mathtt{inl} \circ \langle\rangle_{\Gamma_I[\sigma]} = \Delta' \tag{5.7}$$

Since σ^* is S-preserving.

Case Const:
$$\Delta = [\![\mathtt{k}^{A}]\!] \circ \langle\rangle_{\Gamma_I} \tag{5.8}$$

So

$$\sigma^*(\Delta) = \sigma^*[\![\mathtt{k}^{A}]\!] \circ \langle\rangle_{\Gamma_I[\sigma]} = [\![\mathtt{k}^{A[\sigma]}]\!] \circ \langle\rangle_{\Gamma_I[\sigma]} = \Delta' \tag{5.9}$$

Since σ^* is S-preserving.

Case Subtype: Let
$$\Delta_1 = [\![\Phi \mid \Gamma \vdash v\colon A]\!] \tag{5.10}$$

Then

$$\Delta = [\![A {\le:}_{\Phi} B]\!] \circ \Delta_1 \tag{5.11}$$

So

$$\begin{aligned}\sigma^*(\Delta) &= \sigma^*[\![A {\le:}_{\Phi} B]\!] \circ \sigma^*\Delta_1 \\ &= [\![A[\sigma] {\le:}_{\Phi'} B[\sigma]]\!] \circ \Delta_1' \quad \text{By induction} \\ &= D'\end{aligned}$$

Case Fn: Let
$$\Delta_1 = [\![\Phi \mid \Gamma, x\colon A \vdash v\colon B]\!] \tag{5.12}$$

Then

$$\Delta = \mathtt{cur}(()\Delta_1) \tag{5.13}$$

So

$$\begin{aligned}\sigma^*(\Delta) &= \sigma^*(\mathtt{cur}(\Delta_1)) \\ &= \mathtt{cur}(\sigma^*(\Delta_1)) \quad \text{By S-preservation} \\ &= \mathtt{cur}(\Delta_1') \quad \text{By induction} \\ &= \Delta'\end{aligned}$$

Case Apply: Let

$$\begin{aligned}\Delta_1 &= [\![\Phi \mid \Gamma \vdash v_1\colon A \to B]\!] \\ \Delta_2 &= [\![\Phi \mid \Gamma \vdash v_2\colon A]\!]\end{aligned}$$

Then

$$\Delta = \mathtt{app} \circ \langle \Delta_1, \Delta_2 \rangle \tag{5.14}$$

So

$$
\begin{aligned}
\sigma^*\Delta &= \sigma^*(\mathtt{app} \circ \langle \Delta_1, \Delta_2 \rangle) \\
&= \mathtt{app} \circ \langle \sigma^*(\Delta_1), \sigma^*(\Delta_2) \rangle \quad \text{By S-preservation} \\
&= \mathtt{app} \circ \langle \Delta_1', \Delta_2' \rangle \quad \text{By Induction} \\
&= \Delta'
\end{aligned}
$$

Case Return: Let

$$\Delta_1 = [\![\Phi \mid \Gamma \vdash v \colon A]\!] \tag{5.15}$$

Then

$$\Delta = \eta_{A_I} \circ \Delta_1 \tag{5.16}$$

So

$$
\begin{aligned}
\sigma^*(\Delta) &= \sigma^*(\eta_{A_I} \circ \Delta_1) \\
&= \eta_{A_{I'}} \circ \sigma^*(\Delta_1) \quad \text{By S-preservation} \\
&= \eta_{A_{I'}} \circ \Delta_1' \\
&= \Delta'
\end{aligned}
$$

Case Bind: Let

$$
\begin{aligned}
\Delta_1 &= [\![\Phi \mid \Gamma \vdash v_1 \colon \mathtt{M}_{\epsilon_1} A]\!] \\
\Delta_2 &= [\![\Phi \mid \Gamma, x \colon A \vdash v_2 \colon \mathtt{M}_{\epsilon_2} B]\!]
\end{aligned}
$$

Then

$$\Delta = \mathtt{M}_{\epsilon_1} \epsilon_2 A_I \circ T_{\epsilon_1} \Delta_2 \circ \mathtt{t}_{\epsilon_1, \Gamma_I, A_I} \circ \langle \mathtt{Id}_{\Gamma_I}, \Delta_1 \rangle \tag{5.17}$$

So

$$
\begin{aligned}
\sigma^*(\Delta) &= \sigma^*(\mu_{\epsilon_1, \epsilon_2, A} \circ T_{\epsilon_1} \Delta_2 \circ \mathtt{t}_{\epsilon_1, \Gamma, A} \circ \langle \mathtt{Id}_\Gamma, \Delta_1 \rangle) \\
&= \sigma^*(\mu_{\epsilon_1, \epsilon_2, A}) \circ \sigma^*(T_{\epsilon_1} \Delta_2) \circ \sigma^*(\mathtt{t}_{\epsilon_1, \Gamma, A}) \circ \langle \sigma^*(\mathtt{Id}_{\Gamma_I}), \sigma^*(\Delta_1) \rangle \quad \text{By S-Closure} \\
&= \mu_{\sigma(\epsilon_1), \sigma(\epsilon_2), A[\sigma]'} \circ T_{\sigma(\epsilon_1)} \sigma^*(\Delta_2) \circ \mathtt{t}_{\sigma(\epsilon_1), \Gamma[\sigma], A[\sigma]} \circ \langle \sigma^*(\mathtt{Id}_{\Gamma_I}), \sigma^*(\Delta_1) \rangle \quad \text{By S-Closure} \\
&= \mu_{\sigma(\epsilon_1), \sigma(\epsilon_2), A[\sigma]'} \circ T_{\sigma(\epsilon_1)} \Delta_2' \circ \mathtt{t}_{\sigma(\epsilon_1), \Gamma[\sigma], A[\sigma]} \circ \langle \sigma^*(\mathtt{Id}_{\Gamma_I}), \Delta_1' \rangle \quad \text{By Induction} \\
&= \Delta'
\end{aligned}
$$

Case If: Let

$$
\begin{aligned}
\Delta_1 &= [\![\Phi \mid \Gamma \vdash v \colon \mathtt{Bool}]\!] \\
\Delta_2 &= [\![\Phi \mid \Gamma \vdash v_1 \colon A]\!] \\
\Delta_3 &= [\![\Phi \mid \Gamma \vdash v_2 \colon A]\!]
\end{aligned}
$$

Then

$$\Delta = \mathtt{app} \circ (([\mathtt{cur}(\Delta_2 \circ \pi_2), \mathtt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \tag{5.18}$$

So

$$\begin{aligned}
\sigma^*(\Delta) &= \sigma^*(\mathtt{app} \circ (([\mathtt{cur}(\Delta_2 \circ \pi_2), \mathtt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma) \\
&= \mathtt{app} \circ (([\mathtt{cur}(\sigma^*(\Delta_2) \circ \pi_2), \mathtt{cur}(\sigma^*(\Delta_3) \circ \pi_2)] \circ \sigma^*(\Delta_1)) \times \mathtt{Id}_{\Gamma[\sigma]}) \circ \delta_{\Gamma[\sigma]} \quad \text{By S-Closure} \\
&= \mathtt{app} \circ (([\mathtt{cur}(\Delta_2' \circ \pi_2), \mathtt{cur}(\Delta_3' \circ \pi_2)] \circ \Delta_1') \times \mathtt{Id}_{\Gamma[\sigma]}) \circ \delta_{\Gamma[\sigma]} \quad \text{By Induction} \\
&= \Delta'
\end{aligned}$$

Case Effect-Gen: Let

$$\Delta_1 = [\![\Phi, \alpha \mid \Gamma \vdash v \colon A]\!] \tag{5.19}$$

Then

$$\Delta = \widehat{\Delta_1} \tag{5.20}$$

And also

$$\sigma \times \mathtt{Id} = [\![(\Phi', \alpha) \vdash (\sigma, \alpha \colon= \epsilon) \colon (\Phi, \alpha)]\!] \tag{5.21}$$

So

$$\begin{aligned}
\sigma^* \Delta &= \sigma^*(\widehat{\Delta_1}) \\
&= \widehat{(\sigma \times \mathtt{Id}_U)^* \Delta_1} \quad \text{By naturality} \\
&= \widehat{\Delta_1'} \quad \text{By induction} \\
&= \Delta'
\end{aligned}$$

Case Effect-Spec: Let

$$\begin{aligned}
\Delta_1 &= [\![\Phi \mid \Gamma \vdash v \colon \forall \alpha . A]\!] \\
h &= [\![\Phi \vdash \epsilon \colon \mathtt{Effect}]\!]
\end{aligned}$$

Then

$$\Delta = \langle \mathtt{Id}_\Gamma, h \rangle^* (\epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] \colon \mathtt{Type}]\!]}) \circ \Delta_1 \tag{5.22}$$

So Due to the substitution theorem on effects

$$h \circ \sigma = [\![\Phi \vdash \epsilon \colon \mathtt{Effect}]\!] \circ \sigma = [\![\Phi' \vdash \sigma(\epsilon) \colon \mathtt{Effect}]\!] = h' \tag{5.23}$$

$$\begin{aligned}
\sigma^*\Delta &= \sigma^*(\langle \mathtt{Id}_\Gamma, h\rangle^*(\epsilon_{[\![\Phi,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]}) \circ \Delta_1) \\
&= ((\langle \mathtt{Id}_\Gamma, h\rangle \circ \sigma)^*(\epsilon_{[\![\Phi,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]}) \circ \sigma^*(\Delta_1) \\
&= (((\sigma \times \mathtt{Id}_U) \circ \langle \mathtt{Id}_\Gamma, h\circ\sigma\rangle)^*(\epsilon_{[\![\Phi,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]}) \circ \Delta_1') \\
&= ((\langle \mathtt{Id}_\Gamma, h'\rangle)^*((\sigma \times \mathtt{Id}_U)^*\epsilon_{[\![\Phi,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]}) \circ \Delta_1')
\end{aligned}$$

Looking at the inner part of the functor application: Let

$$A = [\![\Phi, \beta \vdash A[\beta/\alpha]\colon \mathtt{Type}]\!]$$

$$\begin{aligned}
(\sigma \times \mathtt{Id}_U)^*\epsilon_{[\![\Phi,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]} &= (\sigma \times \mathtt{Id}_U)^*\epsilon_A \\
&= (\sigma \times \mathtt{Id}_U)^*(\widehat{\mathtt{Id}_{\forall_I(A)}}) \\
&= \overline{\widehat{(\sigma \times \mathtt{Id}_U)^*(\widehat{\mathtt{Id}_{\forall_I(A)}})}} \quad \text{By bijection} \\
&= \overline{\widehat{\sigma^*(\widehat{\mathtt{Id}_{\forall_I(A)}})}} \quad \text{By naturality} \\
&= \widehat{\sigma^*(\mathtt{Id}_{\forall_I(A)})} \quad \text{By bijection} \\
&= \widehat{\mathtt{Id}_{\forall_{I'}(A\circ(\sigma\times\mathtt{Id}_U))}} \quad \text{By S-Closure, naturality} \\
&= \widehat{\mathtt{Id}_{\forall_{I'}(A[\sigma,\alpha:=\alpha])}} \quad \text{By Substitution theorem} \\
&= \epsilon_{A[\sigma]}
\end{aligned}$$

Going back to the original expression:

$$\begin{aligned}
\sigma^*\Delta &= ((\langle \mathtt{Id}_\Gamma, h'\rangle)^*(\epsilon_{A[\sigma]}) \circ \Delta_1') \\
&= \Delta'
\end{aligned}$$

Chapter 6

Effect Weakening Theorem

In this section, we state and prove a theorem that the action of a simultaneous effect-weakening upon a structure in the language has a consistent effect upon the denotation of the language. More formally, for the denotation morphism Δ of some relation, the denotation of the weakened relation, $\Delta' = \omega^*(\Delta)$.

6.1 Effects

Theorem 6.1.1 (Effect Weakening Preserves Effect Wellformedness). *If* $\omega\colon \Phi' \triangleright \Phi$ *then* $\Phi\epsilon \implies \Phi'\epsilon$

Proof: By induction over the wellformedness of effects

Case E-Ground: By inversion, $\Phi \ \mathtt{Ok} \wedge \epsilon \in E$. Hence by the ok-property, $\Phi' \ \mathtt{Ok}$ So $\Phi'\epsilon$

Case E-Var: $\Phi = \Phi'', \alpha$

So either:

Case: $\Phi' = \Phi''', \alpha$ So $\omega = \omega' \times$ So $\omega'\colon \Phi''' \triangleright \Phi''$, and hence:

$$(\text{E-Var})\frac{\Phi''', \alpha \ \mathtt{Ok}}{\Phi''', \alpha\alpha} \tag{6.1}$$

Case: $\Phi' = \Phi''', \beta$ and $\beta \neq \alpha$

So $\omega = \omega'\pi$

By induction, $\omega'\colon \Phi''' \triangleright \Phi$ so

$$(\text{E-Weaken})\frac{\Phi'''\alpha}{\Phi'\alpha} \tag{6.2}$$

Case E-Weaken: By inversion, $\Phi = \Phi'', \beta$.

So $\omega = \omega' \times$

And, $\Phi' = \Phi''', \beta$ So By inversion, $\omega' \colon \Phi''' \triangleright \pi_1''$

So by induction

$$(\text{E-Weaken})\frac{\Phi'''\alpha}{\Phi'\alpha} \tag{6.3}$$

Case E-Compose: By inversion, $\Phi\epsilon_1$ and $\Phi\epsilon_2$. So by induction, $\Phi'\epsilon_1$ and $\Phi'\epsilon_2$, and so:

$$\Phi'\epsilon_1 \cdot \epsilon_2 \tag{6.4}$$

Theorem 6.1.2 (Effect-Environment Weakening and Effect Denotations). *If* $\omega = [\![\omega \colon \Phi' \triangleright \Phi]\!]$ *then* $\Phi' \vdash \epsilon \colon \mathit{Effect} = \omega^*[\![\Phi \vdash \epsilon \colon \mathit{Effect}]\!] = [\![\Phi \vdash \epsilon \colon \mathit{Effect}]\!] \circ \omega$

Proof: By induction on the derivation on $[\![\Phi \vdash \epsilon \colon \texttt{Effect}]\!]$

Case T-Ground:

$$\begin{aligned}
[\![\Phi \vdash e \colon \texttt{Effect}]\!] \circ \omega &= [\![e]\!] \circ \langle\rangle_I \circ \omega \\
&= [\![e]\!] \circ \langle\rangle_{I'} \\
&= [\![\Phi' \vdash e \colon \texttt{Type}]\!]
\end{aligned}$$

Case E-Var: Case split on ω.

Case: $\omega = \iota$ Then $\Phi' = \Phi$ and $\omega = \texttt{Id}_I$. So the theorem holds trivially.

Case: $\omega = \omega' \times$ Then

$$\begin{aligned}
[\![\Phi, \alpha \vdash \alpha \colon \texttt{Effect}]\!] \circ \omega &= \pi_2 \circ (\omega' \times \texttt{Id}_U) \\
&= \pi_2 \\
&= [\![\Phi', \alpha \vdash \alpha \colon \texttt{Effect}]\!]
\end{aligned}$$

Case: $\omega = \omega'\pi_1$ Then

$$[\![\Phi, \alpha \vdash \alpha \colon \texttt{Effect}]\!] = \pi_2 \circ \omega' \circ \pi_1 \tag{6.5}$$

Where $\Phi' = \Phi, \beta$ and $\omega' \colon \Phi'' \triangleright \Phi$.

So

$$\begin{aligned}
\pi_2 \circ \omega' &= [\![\Phi'' \vdash \alpha \colon \texttt{Effect}]\!] \\
\pi_2 \circ \omega' \circ \pi_1 &= [\![\Phi'', \beta \vdash \alpha \colon \texttt{Effect}]\!] \qquad = [\![\Phi' \vdash \alpha \colon \texttt{Effect}]\!]
\end{aligned}$$

Case E-Weaken:

$$[\![\Phi, \beta \vdash \alpha : \texttt{Effect}]\!] \circ \omega = [\![\Phi \vdash \alpha : \texttt{Effect}]\!] \circ \pi_1 \circ \omega \tag{6.6}$$

Case split of structure of w

Case: $\omega = \iota$ Then $\Phi' = \Phi, \beta$ so $\omega = \texttt{Id}_I$ So $[\![\Phi, \beta \vdash \alpha : \texttt{Effect}]\!] \circ \omega = [\![\Phi' \vdash \alpha : \texttt{Effect}]\!]$

Case: $\omega = \omega'\pi_1$ Then $\Phi' = \Phi'', \gamma$ and $\omega = \omega' \circ \pi_1$ Where $\omega' : \Phi'' \triangleright \Phi, \beta$. So

$$\begin{aligned}
[\![\Phi, \beta \vdash \alpha : \texttt{Effect}]\!] \circ \omega &= [\![\Phi, \beta \vdash \alpha : \texttt{Effect}]\!] \circ \omega' \circ \pi_1 \\
&= \Phi'' \vdash \alpha : \texttt{Effect} \circ \pi_1 \\
&= \Phi'', \gamma \vdash \alpha : \texttt{Effect} \\
&= \Phi' \vdash \alpha : \texttt{Effect}
\end{aligned}$$

Case: $\omega = \omega' \times$ Then $\Phi' = \Phi'', \beta$ and $\omega' : \Phi' \triangleright \Phi$

So

$$\begin{aligned}
[\![\Phi, \beta \vdash \alpha : \texttt{Effect}]\!] \circ \omega &= [\![\Phi \vdash \alpha : \texttt{Effect}]\!] \circ \pi_1 \circ (\omega' \times \texttt{Id}_U) \\
&= [\![\Phi \vdash \alpha : \texttt{Effect}]\!] \circ \omega' \circ \pi_1 \\
&= [\![\Phi'' \vdash \alpha : \texttt{Effect}]\!] \circ \pi_1 \\
&= [\![\Phi' \vdash \alpha : \texttt{Effect}]\!]
\end{aligned}$$

Case E-Compose:

$$\begin{aligned}
[\![\Phi \vdash \epsilon_1 \cdot \epsilon_2 : \texttt{Type}]\!] \circ \omega &= \texttt{Mul}_I([\![\Phi \vdash \epsilon_1 : \texttt{Effect}]\!], [\![\Phi \vdash \epsilon_2 : \texttt{Effect}]\!]) \circ \omega \\
&= \texttt{Mul}_{I'}([\![\Phi \vdash \epsilon_1 : \texttt{Effect}]\!] \circ \omega, [\![\Phi \vdash \epsilon_2 : \texttt{Effect}]\!] \circ \omega) \quad \text{By Naturality} \\
&= \texttt{Mul}_{I'}([\![\Phi' \vdash \epsilon_1 : \texttt{Effect}]\!], [\![\Phi \vdash \epsilon_2 : \texttt{Effect}]\!]) \\
&= [\![\Phi \vdash \epsilon_1 \cdot \epsilon_2 : \texttt{Effect}]\!]
\end{aligned}$$

6.2 Types

Theorem 6.2.1 (Effect-Environment Weakening Preserves Type Wellformedness)**.** *If* $\omega : \Phi' \triangleright \Phi$ *and* ΦA *then* $\Phi' A$*.*

Proof:

Case T-Ground: By inversion, Φ $\texttt{Ok}$, hence by property 1 of weakening, Φ' $\texttt{Ok}$. Hence $\Phi'\gamma$.

Case T-Fn: By inversion, ΦA, ΦB. So by induction $\Phi' A$, $\Phi' B$, hence,

$$\Phi' A \to B$$

Case T-Effect: By inversion, ΦA, and $\Phi \epsilon$.

So by induction and the effect-wellformedness theorem,

$\Phi' A$ and $\Phi' \epsilon$

So

$$\Phi' \mathtt{M}_\epsilon A$$

Case T-Quantification: By inversion, $\Phi, \alpha A$ Picking $\alpha \notin \Phi'$ using α-conversion.

So $\omega \times : (\Phi', \alpha) \triangleright (\Phi, \alpha)$

So $(\Phi', \alpha) A$

So $\Phi \forall \alpha. A$

Theorem 6.2.2 (Effect-Environment Weakening and Type Denotations)**.** *If* $\omega = [\![\Phi' \vdash \omega : \Phi]\!]$ *then* $[\![\Phi' \vdash A : \mathtt{Type}]\!] = \omega^* [\![\Phi \vdash A : \mathtt{Type}]\!]$.

Proof: By induction on the derivation on $[\![\Phi \vdash A : \mathtt{Type}]\!]$. Making use of the S-Closure of the re-indexing functor.

Case T-Ground:

$$\begin{aligned}
\omega^* [\![\Phi \vdash \gamma : \mathtt{Type}]\!] &= \omega^* [\![\gamma]\!] \\
&= [\![\gamma]\!] \quad \text{By S-Closure} \\
&= [\![\Phi' \vdash \gamma : \mathtt{Type}]\!]
\end{aligned}$$

Case T-Effect:

$$\begin{aligned}
\omega^* [\![\Phi \vdash \mathtt{M}_\epsilon A : \mathtt{Type}]\!] \circ \omega &= \omega^* (T_{[\![\Phi \vdash \epsilon : \mathtt{Effect}]\!]} [\![\Phi \vdash A : \mathtt{Type}]\!]) \\
&= T_{\omega^*([\![\Phi \vdash \epsilon : \mathtt{Effect}]\!])} \omega^* ([\![\Phi \vdash A : \mathtt{Type}]\!]) \\
&= [\![\Phi' \vdash \mathtt{M}_\epsilon A : \mathtt{Type}]\!]
\end{aligned}$$

Case T-Quantification:

$$\begin{aligned}
\omega^* [\![\Phi \vdash \forall \alpha. A : \mathtt{Type}]\!] &= \omega^* (\forall_I ([\![\Phi, \alpha \vdash A : \mathtt{Type}]\!])) \\
&= \forall_I ((\omega \times \mathtt{Id}_U)^* [\![\Phi, \alpha \vdash A : \mathtt{Type}]\!]) \quad \text{By Beck-Chevalley} \\
&= \forall_I ([\![\Phi', \alpha \vdash A : \mathtt{Type}]\!]) \\
&= \forall_I ([\![\Phi', \alpha \vdash A : \mathtt{Type}]\!]) \\
&= [\![\Phi' \vdash \forall \alpha. A : \mathtt{Type}]\!]
\end{aligned}$$

Case T-Fn:

$$\begin{aligned}\omega^*[\![\Phi \vdash A \to B\colon \mathtt{Type}]\!] &= \omega^*([\![\Phi \vdash B\colon \mathtt{Type}]\!]^{[\![\Phi \vdash A:\mathtt{Type}]\!]})\\ &= \omega^*([\![\Phi \vdash B\colon \mathtt{Type}]\!])^{\omega^*([\![\Phi \vdash A:\mathtt{Type}]\!])}\\ &= [\![\Phi' \vdash B\colon \mathtt{Type}]\!]^{[\![\Phi' \vdash A:\mathtt{Type}]\!]}\\ &= [\![\Phi' \vdash A \to B\colon \mathtt{Type}]\!]\end{aligned}$$

6.3 Subtyping

Theorem 6.3.1 (Effect-Environment Weakening Preserves Subtyping Relations)**.** *If* $\omega\colon \Phi' \triangleright \Phi$ *and* $A {\leq:}_{\Phi} B$ *then* $A {\leq:}_{\Phi'} B$*.*

Proof:

Case S-Ground: By inversion, $A {\leq:}_{\gamma} B$, so $A {\leq:}_{\Phi'} B$

Case S-Fn: By inversion, $A' {\leq:}_{\Phi} A$ and $B {\leq:}_{\Phi} B'$, so by induction $A' {\leq:}_{\Phi'} A$ and $B {\leq:}_{\Phi'} B'$, so $A \to B {\leq:}_{\Phi'} A' \to B'$.

Case S-Quantification: By inversion, $A {\leq:}_{\Phi,\alpha} A'$. So since $\omega \times\colon \Phi', \alpha \triangleright \Phi, \alpha$, by induction, $A {\leq:}_{\Phi',\alpha} A'$, so $\forall \alpha. A {\leq:}_{\Phi'} \forall \alpha. A'$.

Case S-Effect: By inversion, $A {\leq:} A'$ and $e \leq_{\Phi} e'$. By induction $A {\leq:}_{\Phi'} A'$ and by the weakening-subeffecting theorem, $e \leq_{\Phi'} e'$, so $\mathtt{M}_{\epsilon} A {\leq:}_{\Phi'} \mathtt{M}_{\epsilon'} A'$

Theorem 6.3.2 (Effect-Environment Weakening and Subtype Denotations)**.** *If* $\omega = [\![\omega\colon \Phi' \triangleright \Phi]\!]$ *then* $[\![A {\leq:}_{\Phi'} B]\!] = \omega^*[\![A {\leq:}_{\Phi} B]\!] : \mathbb{C}(I')(A, B)$*.*

Proof: By induction on the derivation on $[\![A {\leq:}_{\Phi} B]\!]$. Using S-preserving property of ω^*

Case T-Ground:

$$\omega^*(\gamma_1 {\leq:}_{\gamma} \gamma_2) = (\gamma_1 {\leq:}_{\gamma} \gamma_2)$$

Since ω^* is s-closed.

Case S-Effect:

$$\begin{aligned}\omega^*[\![\mathtt{M}_{\epsilon_1} A \leq:_\Phi \mathtt{M}_{\epsilon_2} B]\!] &= \omega^*([\![\epsilon_1 \leq_\Phi \epsilon_2]\!]) \circ \omega^*(T_{\epsilon_1}([\![A \leq:_\Phi B]\!]))\\ &= [\![\epsilon_1 \leq_{\Phi'} \epsilon_2]\!] \circ T_{\epsilon_1}[\![A \leq:_{\Phi'} B]\!] \quad \text{By S-Closure}\\ &= [\![\mathtt{M}_{\epsilon_1} A \leq:_{\Phi'} \mathtt{M}_{\epsilon_2} B]\!]\\ &= [\![(\mathtt{M}_{\epsilon_1} A) \leq:_{\Phi'} \mathtt{M}_{\epsilon_2} B]\!]\end{aligned}$$

Case S-Quantification: Note $[\![\omega \times : \Phi', \alpha \triangleright \Phi, \alpha]\!] = (\omega \times \mathtt{Id}_U)$

$$\begin{aligned}\omega^*[\![\forall\alpha.A \leq:_\Phi \forall\alpha.B]\!] &= \omega^*(\forall_I([\![A \leq:_{\Phi,\alpha} B]\!]))\\ &= \forall_{I'}((\omega \times \mathtt{Id}_U)^*([\![A \leq:_{\Phi,\alpha} B]\!]))\\ &= \forall_{I'}([\![A \leq:_{\Phi',\alpha} B]\!])\\ &= [\![(\forall\alpha.A) \leq:_{\Phi'} (\forall\alpha.B)]\!]\end{aligned}$$

Case S-Fn:

$$\begin{aligned}\omega^*[\![(A \to B) \leq:_\Phi A' \to B']\!] &= \omega^*([\![B \leq:_\Phi B']\!]^{A'} \circ B^{[\![A' \leq:_\Phi A]\!]})\\ &= \omega^*(\mathtt{cur}([\![B \leq:_\Phi B']\!] \circ \mathtt{app})) \circ \omega^*(\mathtt{cur}(\mathtt{app} \circ (\mathtt{Id}_B \times [\![A' \leq:_\Phi A]\!])))\\ &= \mathtt{cur}(\omega^*([\![B \leq:_\Phi B']\!]) \circ \mathtt{app}) \circ \mathtt{cur}(\mathtt{app} \circ (\mathtt{Id}_B \times \omega^*([\![A' \leq:_\Phi A]\!])))\\ &= \mathtt{cur}([\![B \leq:_{\Phi'} B']\!] \circ \mathtt{app}) \circ \mathtt{cur}(\mathtt{app} \circ (\mathtt{Id}_B \times [\![A' \leq:_{\Phi'} A]\!]))\\ &= [\![(A \to B) \leq:_{\Phi'} (A' \to B')]\!]\end{aligned}$$

6.4 Term Environments

Theorem 6.4.1 (Effect-Environment Weakening Preserves Term-Environment Wellformedness)**.** *If* $\omega : \Phi' \triangleright \Phi$ *and* $\Phi \vdash \Gamma\ \mathit{Ok}$ *then* $\Phi' \vdash \Gamma\ \mathit{Ok}$.

Proof:

Case Env-Nil: By inversion, $\Phi\ \mathtt{Ok}$ so $\Phi \vdash \diamond\ \mathtt{Ok}$

Case Env-Extend: By inversion, $\Phi \vdash \Gamma\ \mathtt{Ok}$, $x \in \mathtt{dom}(\Gamma)$, ΦA

So by induction $\Phi' \vdash \Gamma\ \mathtt{Ok}$, and $\pi_1' \vdash \Gamma\ \mathtt{Ok}$

So $\Phi' \vdash (\Gamma, x : A)\ \mathtt{Ok}$

Theorem 6.4.2 (Effect-Environment Weakening and Term-Environment Denotations)**.** *If* $\omega = [\![\Phi' \vdash \omega : \Phi]\!]$ *then* $[\![\Phi' \vdash \Gamma\ \mathit{Ok}]\!] = \omega^*[\![\Phi \vdash \Gamma\ \mathit{Ok}]\!] \in \mathit{obj}\ \mathbb{C}(I')$.

Proof: By induction on the derivation on $[\![\Phi \vdash \Gamma \ \mathtt{Ok}]\!]$. Using the S-Closure of the re-indexing functor.

Case Env-Nil:

$$\begin{aligned}\omega^*[\![\Phi \vdash \diamond \ \mathtt{Ok}]\!] &= \omega^* \mathtt{1} \\ &= \mathtt{1} \quad \text{By S-preservation} \\ &= [\![\Phi' \vdash \diamond \ \mathtt{Ok}]\!]\end{aligned}$$

Case Env-Extend:

$$\begin{aligned}\omega^*[\![\Phi \vdash \Gamma, x\colon A \ \mathtt{Ok}]\!] &= \omega^*([\![\Phi \vdash \Gamma \ \mathtt{Ok}]\!] \times [\![\Phi \vdash A\colon \mathtt{Type}]\!]) \\ &= (\omega^*[\![\Phi \vdash \Gamma \ \mathtt{Ok}]\!] \times \omega^*[\![\Phi \vdash A\colon \mathtt{Type}]\!]) \\ &= ([\![\Phi' \vdash \Gamma \ \mathtt{Ok}]\!] \times [\![\Phi' \vdash A\colon \mathtt{Type}]\!]) \\ &= [\![\Phi' \vdash \Gamma, x : A \ \mathtt{Ok}]\!]\end{aligned}$$

6.5 Terms

Theorem 6.5.1 (Effect-Environment Weakening Preserves Typing Relation). *If* $\Phi \mid \Gamma \vdash v\colon A$ *and* $\omega\colon \Phi' \triangleright \Phi$ *then* $\Phi' \mid \Gamma \vdash v\colon A$

Proof:

Case Const: If $\Phi \vdash \Gamma \ \mathtt{Ok}$ then $\Phi' \vdash \Gamma \ \mathtt{Ok}$ so:

$$(\text{Const})\frac{\Phi' \vdash \Gamma \ \mathtt{Ok}}{\Phi' \mid \Gamma \vdash \mathtt{k}^{A}\colon A} \tag{6.7}$$

Case Variables: If $\Phi \vdash \Gamma \ \mathtt{Ok}$ then $\Phi' \vdash \Gamma \ \mathtt{Ok}$ so: So, $\Phi' \mid G \vdash x\colon A$, if $\Phi \mid G \vdash x\colon A$

Case Fn: By inversion, $\Phi \mid \Gamma, x\colon A \vdash v\colon B$, so by induction $\Phi' \mid \Gamma, x\colon A \vdash v\colon B$.
So,

$$\Phi' \mid \Gamma \vdash \lambda x\colon A.v : A \to B \tag{6.8}$$

Case Apply: By inversion, $\Phi \mid \Gamma \vdash v_1 \colon A \to B$ and $\Phi \mid \Gamma \vdash v_2 \colon A$.

Hence by induction, $\Phi' \mid \Gamma \vdash v_1 \colon A \to B$ and $\Phi' \mid \Gamma \vdash v_2 \colon A$.

So

$$\Phi' \mid \Gamma \vdash \mathtt{app} v_1 v_2 \colon B$$

Case Return: By inversion, $\Phi \mid \Gamma \vdash v \colon A$

So by induction $\Phi' \mid \Gamma \vdash v \colon A$

Hence $\Phi' \mid \Gamma \vdash \mathtt{return}\ v : \mathtt{M}_{\mathtt{1}} A$

Case Bind: By inversion, $\Phi \mid \Gamma \vdash v_1 \colon \mathtt{M}_{\epsilon_1} A$ and $\Phi \mid \Gamma, x \colon A \vdash \epsilon_2 \colon \mathtt{M}_{\epsilon_2} A$.

Hence by induction $\Phi' \mid \Gamma \vdash v_1 \colon \mathtt{M}_{\epsilon_1} A$ and $\Phi' \mid \Gamma, x \colon A \vdash v_2 \colon \mathtt{M}_{\epsilon_2} A$.

So

$$\Phi' \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B \tag{6.9}$$

Case If: By inversion, $\Phi \mid \Gamma \vdash v \colon \mathtt{Bool}$, $\Phi \mid \Gamma \vdash v_1 \colon A$, and $\Phi \mid \Gamma \vdash v_2 \colon A$.

Hence by induction $\Phi' \mid \Gamma \vdash v \colon \mathtt{Bool}$, $\Phi' \mid \Gamma \vdash v_1 \colon A$, and $\Phi' \mid \Gamma \vdash v_2 \colon A$.

So

$$\Phi' \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : A \tag{6.10}$$

Case Subtype: By inversion, $\Phi \mid \Gamma \vdash v \colon A$, and $A {\leq :} B$.

So by induction: $\Phi' \mid \Gamma \vdash v \colon A$, and $A {\leq :} B$.

So

$$\Phi' \mid \Gamma \vdash v \colon B \tag{6.11}$$

Case Effect-Gen: By inversion, $\Phi, \alpha \mid \Gamma \vdash v \colon A$

By picking $\alpha \notin \Phi'$ using α-conversion.

$$\omega \times \colon \Phi', \alpha \triangleright \Phi, \alpha \tag{6.12}$$

So by induction, $\Phi', \alpha \mid \Gamma \vdash v \colon A$

Hence,

$$\Phi' \mid \Gamma \vdash \Lambda \alpha . v \colon \forall a . A \tag{6.13}$$

Case Effect-Spec: By inversion, $\Phi \mid \Gamma \vdash v \colon \forall \alpha . A$, and $\Phi \epsilon$.

So by induction, $\Phi' \mid \Gamma \vdash v \colon \forall \alpha . A$

And by the wellformedness-theorem $\Phi' \epsilon$

Hence,

$$\Phi' \mid \Gamma \vdash v\ \epsilon \colon A[\epsilon / \alpha] \tag{6.14}$$

Theorem 6.5.2 (Effect Environment Weakening). *If*

$$\omega = [\![\omega\colon \Phi' \triangleright \Phi]\!]$$
$$\Delta = [\![\Phi \mid \Gamma \vdash v\colon A]\!]$$
$$\Delta' = [\![\Phi' \mid \Gamma \vdash v\colon A]\!]$$

Then

$$\Delta' = \omega^*(\Delta) \tag{6.15}$$

Proof: By induction over the derivation of Δ. Using the S-Closure of ω^*. We use Γ_I to indicate $[\![\Phi \vdash \Gamma\ \mathtt{Ok}]\!]$, an A_I to indicate $[\![\Phi \vdash A\colon \mathtt{Type}]\!]$

Case Unit:

$$\Delta = \langle\rangle_{\Gamma_I} \tag{6.16}$$

So

$$\omega^*(\Delta) = \langle\rangle_{\Gamma_{I'}} = \Delta' \tag{6.17}$$

Case True, False: Giving the case for true as false is the same but using `inr`

$$\Delta = \mathtt{inl} \circ \langle\rangle_{\Gamma_I} \tag{6.18}$$

So

$$\omega^*(\Delta) = \mathtt{inl} \circ \langle\rangle_{\Gamma_{I'}} = \Delta' \tag{6.19}$$

Since ω^* is S-preserving.

Case Const:

$$\Delta = [\![\mathtt{k}^A]\!] \circ \langle\rangle_{\Gamma_I} \tag{6.20}$$

So

$$\omega^*(\Delta) = \omega^*[\![\mathtt{k}^A]\!] \circ \langle\rangle_{\Gamma_{I'}} = [\![\mathtt{k}^{A_{I'}}]\!] \circ \langle\rangle_{\Gamma_{I'}} = \Delta' \tag{6.21}$$

Since ω^* is S-preserving.

Case Subtype: Let

$$\Delta_1 = [\![\Phi \mid \Gamma \vdash v\colon A]\!] \tag{6.22}$$

Then

$$\Delta = [\![A \leq:_\Phi B]\!] \circ \Delta_1 \tag{6.23}$$

So

$$\begin{aligned}\omega^*(\Delta) &= \omega^*[\![A {\leq:}_{\Phi} B]\!] \circ \omega^* \Delta_1 \\ &= [\![A_{I'} {\leq:}_{\Phi'} B_{I'}]\!] \circ \Delta_1' \quad \text{By induction} \\ &= D'\end{aligned}$$

Case Fn: Let

$$\Delta_1 = [\![\Phi \mid \Gamma, x{:}\, A \vdash v{:}\, B]\!] \tag{6.24}$$

Then

$$\Delta = \mathtt{cur}(\Delta_1) \tag{6.25}$$

So

$$\begin{aligned}\omega^*(\Delta) &= \omega^*(\mathtt{cur}(\Delta_1)) \\ &= \mathtt{cur}(\omega^*(\Delta_1)) \quad \text{By S-preservation} \\ &= \mathtt{cur}(\Delta_1') \quad \text{By induction} \\ &= \Delta'\end{aligned}$$

Case Apply: Let

$$\begin{aligned}\Delta_1 &= [\![\Phi \mid \Gamma \vdash v_1{:}\, A \to B]\!] \\ \Delta_2 &= [\![\Phi \mid \Gamma \vdash v_2{:}\, A]\!]\end{aligned}$$

Then

$$\Delta = \mathsf{app} \circ \langle \Delta_1, \Delta_2 \rangle \tag{6.26}$$

So

$$\begin{aligned}\omega^*\Delta &= \omega^*(\mathsf{app} \circ \langle \Delta_1, \Delta_2 \rangle) \\ &= \mathsf{app} \circ \langle \omega^*(\Delta_1), \omega^*(\Delta_2) \rangle \quad \text{By S-preservation} \\ &= \mathsf{app} \circ \langle \Delta_1', \Delta_2' \rangle \quad \text{By Induction} \\ &= \Delta'\end{aligned}$$

Case Return: Let

$$\Delta_1 = [\![\Phi \mid \Gamma \vdash v{:}\, A]\!] \tag{6.27}$$

Then

$$\Delta = \eta_{A_I} \circ \Delta_1 \tag{6.28}$$

So

$$\begin{aligned}\omega^*(\Delta) &= \omega^*(\eta_{A_I} \circ \Delta_1) \\ &= \eta_{A_{I'}} \circ \omega^*(\Delta_1) \quad \text{By S-preservation} \\ &= \eta_{A_{I'}} \circ \Delta_1' \\ &= \Delta'\end{aligned}$$

Case Bind: Let

$$\begin{aligned}\Delta_1 &= [\![\Phi \mid \Gamma \vdash v_1 : \mathtt{M}_{\epsilon_1} A]\!] \\ \Delta_2 &= [\![\Phi \mid \Gamma, x : A \vdash v_2 : \mathtt{M}_{\epsilon_2} B]\!]\end{aligned}$$

Then

$$\Delta = \mathtt{M}_{\epsilon_1}\epsilon_2 A_I \circ T_{\epsilon_1}\Delta_2 \circ \mathtt{t}_{\epsilon_1,\Gamma_I,A_I} \circ \langle \mathtt{Id}_{\Gamma_I}, \Delta_1 \rangle \tag{6.29}$$

So

$$\begin{aligned}\omega^*(\Delta) &= \omega^*(\mu_{\epsilon_1,\epsilon_2,A} \circ T_{\epsilon_1}\Delta_2 \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, \Delta_1 \rangle) \\ &= \omega^*(\mu_{\epsilon_1,\epsilon_2,A}) \circ \omega^*(T_{\epsilon_1}\Delta_2) \circ \omega^*(\mathtt{t}_{\epsilon_1,\Gamma,A}) \circ \langle \omega^*(\mathtt{Id}_{\Gamma_I}), \omega^*(\Delta_1) \rangle \quad \text{By S-Closure} \\ &= \mu_{\epsilon_1,\epsilon_2,A_{I'}} \circ T_{\epsilon_1}\omega^*(\Delta_2) \circ \mathtt{t}_{\epsilon_1,\Gamma_{I'},A_{I'}} \circ \langle \omega^*(\mathtt{Id}_{\Gamma_I}), \omega^*(\Delta_1) \rangle \quad \text{By S-Closure} \\ &= \mu_{\epsilon_1,\epsilon_2,A_{I'}} \circ T_{\epsilon_1}\Delta_2' \circ \mathtt{t}_{\epsilon_1,\Gamma_{I'},A_{I'}} \circ \langle \omega^*(\mathtt{Id}_{\Gamma_I}), \Delta_1' \rangle \quad \text{By Induction} \\ &= \Delta'\end{aligned}$$

Case If: Let

$$\begin{aligned}\Delta_1 &= [\![\Phi \mid \Gamma \vdash v : \mathtt{Bool}]\!] \\ \Delta_2 &= [\![\Phi \mid \Gamma \vdash v_1 : A]\!] \\ \Delta_3 &= [\![\Phi \mid \Gamma \vdash v_2 : A]\!]\end{aligned}$$

Then

$$\Delta = \mathtt{app} \circ (([\mathtt{cur}(\Delta_2 \circ \pi_2), \mathtt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \tag{6.30}$$

So

$$\begin{aligned}\omega^*(\Delta) &= \omega^*(\mathtt{app} \circ (([\mathtt{cur}(\Delta_2 \circ \pi_2), \mathtt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma) \\ &= \mathtt{app} \circ (([\mathtt{cur}(\omega^*(\Delta_2) \circ \pi_2), \mathtt{cur}(\omega^*(\Delta_3) \circ \pi_2)] \circ \omega^*(\Delta_1)) \times \mathtt{Id}_{\Gamma_{I'}}) \circ \delta_{\Gamma_{I'}} \quad \text{By S-Closure} \\ &= \mathtt{app} \circ (([\mathtt{cur}(\Delta_2' \circ \pi_2), \mathtt{cur}(\Delta_3' \circ \pi_2)] \circ \Delta_1') \times \mathtt{Id}_{\Gamma_{I'}}) \circ \delta_{\Gamma_{I'}} \quad \text{By Induction} \\ &= \Delta'\end{aligned}$$

Case Effect-Gen: Let

$$\Delta_1 = [\![\Phi, \alpha \mid \Gamma \vdash v \colon A]\!] \tag{6.31}$$

Then

$$\Delta = \overline{\Delta_1} \tag{6.32}$$

And also

$$\omega \times \texttt{Id} = [\![\omega \times \colon (\Phi', \alpha) \triangleright (\Phi, \alpha)]\!] \tag{6.33}$$

So

$$\begin{aligned}
\omega^* \Delta &= \omega^* (\overline{\Delta_1}) \\
&= \overline{(\omega \times \texttt{Id}_U)^* \Delta_1} \quad \text{By naturality} \\
&= \overline{\Delta_1'} \quad \text{By induction} \\
&= \Delta'
\end{aligned}$$

Case Effect-Spec: Let

$$\begin{aligned}
\Delta_1 &= [\![\Phi \mid \Gamma \vdash v \colon \forall \alpha . A]\!] \\
h &= [\![\Phi \vdash \epsilon \colon \texttt{Effect}]\!]
\end{aligned}$$

Then

$$\Delta = \langle \texttt{Id}_\Gamma, h \rangle^* (\epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] \colon \texttt{Type}]\!]}) \circ \Delta_1 \tag{6.34}$$

So due to the substitution theorem on effects

$$h \circ \omega = [\![\Phi \vdash \epsilon \colon \texttt{Effect}]\!] \circ \omega = [\![\Phi' \vdash \epsilon \colon \texttt{Effect}]\!] = h' \tag{6.35}$$

Also note $(\omega \times \texttt{Id}_U) = [\![\omega \times \colon \Phi', \alpha \triangleright \Phi \alpha]\!]$

$$\begin{aligned}
\omega^* \Delta &= \omega^* (\langle \texttt{Id}_\Gamma, h \rangle^* (\epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] \colon \texttt{Type}]\!]}) \circ \Delta_1) \\
&= (\langle \texttt{Id}_\Gamma, h \rangle \circ \omega)^* (\epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] \colon \texttt{Type}]\!]}) \circ \omega^* (\Delta_1) \\
&= ((\omega \times \texttt{Id}_U) \circ \langle \texttt{Id}_\Gamma, h \circ \omega \rangle)^* (\epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] \colon \texttt{Type}]\!]}) \circ \Delta_1') \\
&= (\langle \texttt{Id}_\Gamma, h' \rangle)^* ((\omega \times \texttt{Id}_U)^* \epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] \colon \texttt{Type}]\!]}) \circ \Delta_1')
\end{aligned}$$

Looking at the inner part of the functor application: Let

$$A = [\![\Phi, \beta \vdash A[\beta/\alpha] \colon \texttt{Type}]\!]$$

$$
\begin{aligned}
(\omega \times \texttt{Id}_U)^* \epsilon_{[\![\Phi, \beta \vdash A[\beta/\alpha] : \texttt{Type}]\!]} &= (\omega \times \texttt{Id}_U)^* \epsilon_A \\
&= (\omega \times \texttt{Id}_U)^* (\widehat{\texttt{Id}_{\forall_I(A)}}) \\
&= \overline{\overline{(\omega \times \texttt{Id}_U)^* (\widehat{\texttt{Id}_{\forall_I(A)}})}} \quad \text{By bijection} \\
&= \overline{\omega^* (\overline{\widehat{\texttt{Id}_{\forall_I(A)}}})} \quad \text{By naturality} \\
&= \overline{\omega^* (\texttt{Id}_{\forall_I(A)})} \quad \text{By bijection} \\
&= \overline{\texttt{Id}_{\forall_{I'}(A \circ (\omega \times \texttt{Id}_U))}} \quad \text{By S-Closure, naturality} \\
&= \widehat{\texttt{Id}_{\forall_{I'}(A)}} \quad \text{By Substitution theorem} \\
&= \epsilon_{A_{I'}}
\end{aligned}
$$

Going back to the original expression:

$$
\begin{aligned}
\omega^* \Delta &= ((\langle \texttt{Id}_\Gamma, h' \rangle)^* (\epsilon_{A_{I'}}) \circ \Delta'_1) \\
&= \Delta'
\end{aligned}
$$

6.6 Term-Substitution

Theorem 6.6.1 (Effect-Environment Weakening Preserves Term Substitutions)**.** *If* $\omega \colon \Phi' \triangleright \Phi$ *and* $\Phi \mid \Gamma' \vdash \sigma \colon \Gamma$ *then* $\Phi' \mid \Gamma' \vdash \sigma \colon \Gamma$.

Proof: If $\Phi \vdash \Gamma'$ `Ok` then $\Phi' \vdash \Gamma'$ `Ok` For each term v in σ, $\Phi \mid \Gamma' \vdash v \colon A$, which means $\Phi' \mid \vdash \Gamma' \colon vA$. So $\Phi' \mid \Gamma' \vdash \sigma \colon \Gamma$ holds.

Theorem 6.6.2 (Effect-Environment Weakening and Term-Substitution Denotations)**.** *If* $\omega = [\![\omega \colon \Phi' \triangleright \Phi]\!]$, *then* $[\![\Phi' \mid \Gamma' \vdash \sigma \colon \Gamma]\!] = \omega^* [\![\Phi \mid \Gamma' \vdash \sigma \colon \Gamma]\!]$.

Proof: By induction on the structure of σ, making use of the weakening of term denotations above.

Case T-Nil: Then $\sigma = \langle\rangle_{\Gamma'_I}$, so $\omega^*(\sigma) = \langle\rangle_{\Gamma'_{I'}} = [\![\Phi' \mid \Gamma' \vdash \sigma \colon \Gamma]\!]$

Case T-Extend: Then $\sigma = (\sigma', x \colon= v)$

$$
\begin{aligned}
\omega^* \sigma &= \omega * \langle \sigma', [\![\Phi \mid \Gamma \vdash v \colon A]\!] \rangle \\
&= \langle \omega^* \sigma', \omega^* [\![\Phi \mid \Gamma \vdash v \colon A]\!] \rangle \\
&= \langle [\![\Phi' \mid \Gamma' \vdash \sigma' \colon \Gamma]\!], [\![\Gamma' \mid \Phi' \vdash v \colon A]\!] \rangle \\
&= [\![\Phi' \mid \Gamma' \vdash \sigma \colon \Gamma, x \colon A]\!]
\end{aligned}
$$

6.7 Term-Weakening

Theorem 6.7.1 (Effect-Environment Weakening Preserves Term-Environment Weakening). *If* $\omega_1 : \Phi' \triangleright \Phi$ *and* $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$ *then* $\Phi' \vdash \omega : \Gamma' \triangleright \Gamma$.

Proof:

Case T-Id: By inversion, $\Phi \vdash \Gamma$ $\mathtt{Ok}$, so $\Phi' \vdash \Gamma$ $\mathtt{Ok}$, so $\Phi' \vdash \omega : \Gamma \triangleright \Gamma$.

Case T-Project: By inversion, $\Phi \vdash A$ $\mathtt{Ok}$ and $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$, so by induction and the preservation of wellformedness of types, $\Phi' \vdash A$ $\mathtt{Ok}$ and $\Phi' \vdash \omega : \Gamma' \triangleright \Gamma$. Hence $\Phi' \vdash \omega\pi_1 : \Gamma', x : A \triangleright \Gamma$

Case T-Extend: By inversion, $\Phi \vdash A$ $\mathtt{Ok}$ and $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$, $A \leq :_\Phi B$. So by induction and the preservation of wellformedness of types, $\Phi' \vdash A$ $\mathtt{Ok}$ and $\Phi' \vdash \omega : \Gamma' \triangleright \Gamma$, $A \leq :_{\Phi'} B$. Since $A \leq :_{\Phi'} B$, $\Phi' B$. Hence $\Phi' \vdash \omega\times : \Gamma', x : A \triangleright \Gamma : B$.

Theorem 6.7.2 (Effect Weakening and Term Weakening Denotations). *If* $\Phi' \vdash \omega_1 : \Gamma' \triangleright \Gamma$ *and* $\omega = [\![\omega : \Phi' \triangleright \Phi]\!]$, *then* $\Phi' \vdash \omega_1 : \Gamma' \triangleright \Gamma$ *and* $[\![\Phi' \vdash \omega_1 : \Gamma' \triangleright \Gamma]\!] = \omega^*[\![\Phi \vdash \omega_1 : \Gamma' \triangleright \Gamma]\!]$.

Proof: By induction on the structure of ω_1.

Case T-Id: Then $\omega_1 = \iota$, so its denotation is $\omega_1 = \mathtt{Id}_{\Gamma_I}$

So

$$\omega^*(\mathtt{Id}_{\Gamma_I}) = \mathtt{Id}_{\Gamma_{I'}} = [\![\Phi' \vdash \iota : \Gamma \triangleright \Gamma]\!] \tag{6.36}$$

Case T-Project: Then $\omega_1 = \omega_1'\pi$

$$(\text{T-Project})\frac{\Phi \vdash \omega_1' : \Gamma' \triangleright \Gamma}{\Phi \vdash \omega_1\pi : \Gamma', x : A \triangleright \Gamma} \tag{6.37}$$

So $\omega_1 = \omega_1' \circ \pi_1$

Hence

$$\begin{aligned}\omega^*(\omega_1) &= \omega^*(\omega_1') \circ \omega^*(\pi_1)\\ &= [\![\Phi' \vdash \omega_1' : \Gamma' \triangleright \Gamma]\!] \circ \pi_1\\ &= [\![\Phi' \vdash \omega_1'\pi : \Gamma', x : A \triangleright \Gamma]\!]\\ &= [\![\Phi' \vdash \omega_1 : \Gamma', x : A \triangleright \Gamma]\!]\end{aligned}$$

Case T-Extend: Then $\omega_1 = \omega_1' \times$

$$(\text{T-Extend})\frac{\Phi \vdash \omega_1' : \Gamma' \triangleright \Gamma \qquad A \leq :_\Phi B}{\Phi \vdash \omega_1 \times : \Gamma', x : A \triangleright \Gamma, x : B} \tag{6.38}$$

So $\omega_1 = \omega_1' \times [\![A {\leq:}_{\Phi} B]\!]$

Hence

$$\begin{aligned}
\omega^*(\omega_1) &= (\omega^*(\omega_1') \times \omega^*([\![A {\leq:}_{\Phi} B]\!]) \\
&= ([\![\Phi' \vdash \omega_1' \colon \Gamma' \triangleright \Gamma]\!] \times [\![A {\leq:}_{\Phi'} B]\!]) \\
&= [\![\Phi' \vdash \omega_1 \colon \Gamma', x : A \triangleright \Gamma, x : B]\!]
\end{aligned}$$

Chapter 7

Term Substitution Theorem

Theorem 7.0.1 (Term Substitution)**.** *If* Δ *derives* $\Phi \mid \Gamma \vdash v\colon A$ *and* $\Phi \mid \Gamma' \vdash \sigma\colon \Gamma$ *then the derivation* Δ' *deriving* $\Phi \mid \Gamma' \vdash v[\sigma]\colon A$ *satisfies:*

$$\Delta' = \Delta \circ [\![\Phi \mid \Gamma' \vdash \sigma\colon \Gamma]\!] \tag{7.1}$$

Proof: This is proved by induction over the derivation of $\Phi \mid \Gamma \vdash v\colon A$. We shall use σ to denote $[\![\Phi \mid \Gamma' \vdash \sigma\colon \Gamma]\!]$ where it is clear from the context.

Case Var: By inversion, $\Gamma = \Gamma'', x : A$

$$(\text{Var})\frac{\Phi \vdash \Gamma \ \ \texttt{Ok}}{\Phi \mid \Gamma'', x : A \vdash x\colon A} \tag{7.2}$$

By inversion, $\sigma = \sigma', x\colon= v$ and $\Phi \mid \Gamma' \vdash v\colon A$.

Let

$$\begin{aligned} \sigma &= [\![\Phi \mid \Gamma' \vdash \sigma\colon \Gamma]\!] = \langle \sigma', \Delta' \rangle \\ \Delta &= [\![\Phi \mid \Gamma'', x : A \vdash x\colon A]\!] = \pi_2 \end{aligned}$$

$$\begin{aligned} \Delta \circ \sigma &= \pi_2 \circ \langle \sigma', \Delta' \rangle && \text{By definition} \\ &= \Delta' && \text{By product property} \end{aligned}$$

Case Weaken: By inversion, $\Gamma = \Gamma', y : B$ and $\sigma = \sigma', y\colon= v$ and we have Δ_1 deriving:

$$(\text{Weaken})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma'' \vdash x\colon A}}{\Phi \mid \Gamma'', y : B \vdash x\colon A} \tag{7.3}$$

Also by inversion of the wellformedness of $\Phi \mid \Gamma' \vdash \sigma\colon \Gamma$, we have $\Phi \mid \Gamma' \vdash \sigma'\colon \Gamma''$ and

$$[\![\Phi \mid \Gamma' \vdash \sigma : \Gamma]\!] = \langle [\![\Phi \mid \Gamma' \vdash \sigma : \Gamma'']\!], [\![\Phi \mid \Gamma' \vdash v : B]\!] \rangle \tag{7.4}$$

Hence by induction on Δ_1 we have Δ_1' such that

$$\frac{\Delta_1'}{\Phi \mid \Gamma' \vdash x[\sigma] : A} \tag{7.5}$$

Hence

$$\begin{aligned}
\Delta' &= \Delta_1' \quad \text{By definition} \\
&= \Delta_1 \circ \sigma' \quad \text{By induction} \\
&= \Delta_1 \circ \pi_1 \circ \langle \sigma', [\![\Phi \mid \Gamma' \vdash v : B]\!] \rangle \quad \text{By product property} \\
&= \Delta_1 \circ \pi_1 \circ \sigma \quad \text{By defintion of the denotation of } \sigma \\
&= \Delta \circ \sigma \quad \text{By defintion.}
\end{aligned}$$

Case Const: The logic for all constant terms ($\texttt{true}, \texttt{false}, \texttt{()}, \texttt{k}^A$) is the same. Let

$$c = [\![\texttt{k}^A]\!] \tag{7.6}$$

$$\begin{aligned}
\Delta' &= c \circ \langle\rangle_{\Gamma'} \quad \text{By Definition} \\
&= c \circ \langle\rangle_G \circ \sigma \quad \text{Terminal property} \\
&= \Delta \circ \sigma \quad \text{By definition}
\end{aligned}$$

Case Fn: By inversion, we have Δ_1 such that

$$\Delta = (\mathrm{Fn})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma, x : A \vdash v : B}}{\Phi \mid \Gamma \vdash \lambda x : A.v : A \to B} \tag{7.7}$$

By induction of Δ_1 we have Δ_1' such that

$$\Delta' = (\mathrm{Fn})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma', x : A \vdash (v[\sigma]) : B}}{\Phi \mid \Gamma \vdash (\lambda x : A.v\ )[\sigma] : A \to B} \tag{7.8}$$

By induction and the extension lemma, we have:

$$\Delta_1' = \Delta_1 \circ (\sigma \times \texttt{Id}_A) \tag{7.9}$$

Hence:

$$\begin{aligned}
\Delta' &= \texttt{cur}(\Delta_1') \quad \text{By definition} \\
&= \texttt{cur}(\Delta_1 \circ (\sigma \times \texttt{Id}_A)) \quad \text{By induction and extension lemma.} \\
&= \texttt{cur}(\Delta_1) \circ \sigma \quad \text{By the exponential property (Uniqueness)} \\
&= \Delta \circ \sigma \quad \text{By Definition}
\end{aligned}$$

Case Subtype: By inversion, there exists derivation Δ_1 such that:

$$\Delta = (\text{Subtype})\dfrac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v \colon A} \qquad A {\leq:_\Phi} B}{\Phi \mid \Gamma \vdash v \colon B} \tag{7.10}$$

By induction on Δ_1, we find Δ_1' such that $\Delta_1' = \Delta_1 \circ \sigma$ and:

$$\Delta' = (\text{Subtype})\dfrac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v[\sigma] \colon A} \qquad A {\leq:_\Phi} B}{\Phi \mid \Gamma' \vdash v[\sigma] \colon B} \tag{7.11}$$

Hence,

$$\begin{aligned}
\Delta' &= [\![A {\leq:_\Phi} B]\!] \circ \Delta_1' \quad \text{By definition} \\
&= [\![A {\leq:_\Phi} B]\!] \circ \Delta_1 \circ \sigma \quad \text{By induction} \\
&= \Delta \circ \sigma \quad \text{By definition}
\end{aligned}$$

Case Return: By inversion, we have Δ_1 such that:

$$\Delta = (\text{Return})\dfrac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v \colon A}}{\Phi \mid \Gamma \vdash \texttt{return}\ v : \texttt{M}_{\texttt{1}} A} \tag{7.12}$$

By induction on Δ_1, we find Δ_1' such that $\Delta_1' = \Delta_1 \circ \sigma$ and:

$$\Delta' = (\text{Return})\dfrac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v[\sigma] \colon A}}{\Phi \mid \Gamma' \vdash (\texttt{return}\ v\ )[\sigma] \colon \texttt{M}_{\texttt{1}} A} \tag{7.13}$$

Hence,

$$\begin{aligned}
\Delta' &= \eta_A \circ \Delta_1' \quad \text{By Definition} \\
&= \eta_A \circ \Delta_1 \circ \sigma \quad \text{By induction} \\
&= \Delta \circ \sigma \quad \text{By Definition}
\end{aligned}$$

Case Apply: By inversion, we find Δ_1, Δ_2 such that

$$\Delta = (\text{Apply})\dfrac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v_1 \colon A \to B} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma \vdash v_2 \colon A}}{\Phi \mid \Gamma \vdash v_1\ v_2 \colon B} \tag{7.14}$$

By induction we find Δ_1', Δ_2' such that

$$\Delta_1' = \Delta_1 \circ \sigma$$
$$\Delta_2' = \Delta_2 \circ \sigma$$

And

$$\Delta' = (\text{Apply})\,\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v_1[\sigma]\colon A \to B} \qquad \dfrac{\Delta_2'}{\Phi \mid \Gamma' \vdash v_2[\sigma]\colon A}}{\Phi \mid \Gamma' \vdash (v_1\ v_2)[\sigma]\colon B} \tag{7.15}$$

Hence

$$\begin{aligned}
\Delta' &= \texttt{app} \circ \langle \Delta_1', \Delta_2' \rangle \quad \text{By Definition} \\
&= \texttt{app} \circ \langle \Delta_1 \circ \sigma, \Delta_2 \circ \sigma \rangle \quad \text{By induction} \\
&= \texttt{app} \circ \langle \Delta_1, \Delta_2 \rangle \circ \sigma \quad \text{By Product Property} \\
&= \Delta \circ \sigma \quad \text{By Definition}
\end{aligned}$$

Case If: By inversion, we find $\Delta_1, \Delta_2, \Delta_3$ such that

$$\Delta = (\text{If})\,\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v\colon \texttt{Bool}} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma \vdash v_1\colon A} \qquad \dfrac{\Delta_3}{\Phi \mid \Gamma \vdash v_2\colon A}}{\Phi \mid \Gamma \vdash \texttt{if}_A\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2 : A} \tag{7.16}$$

By induction we find $\Delta_1', \Delta_2', \Delta_3'$ such that

$$\Delta_1' = \Delta_1 \circ \sigma$$
$$\Delta_2' = \Delta_2 \circ \sigma$$
$$\Delta_3' = \Delta_3 \circ \sigma$$

And

$$\Delta' = (\text{If})\,\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v[\sigma]\colon \texttt{Bool}} \qquad \dfrac{\Delta_2'}{\Phi \mid \Gamma' \vdash v_1[\sigma]\colon A} \qquad \dfrac{\Delta_3'}{\Phi \mid \Gamma' \vdash v_2[\sigma]\colon A}}{\Phi \mid \Gamma' \vdash (\texttt{if}_A\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2\ )[\sigma]\colon A} \tag{7.17}$$

Since $\sigma : \Gamma' \to \Gamma$, let $(T_\epsilon A)^\sigma : T_\epsilon A^\Gamma \to T_\epsilon A^{\Gamma'}$ be as defined in ExSh 3 ([1]) That is:

$$(T_\epsilon A)^\sigma = \texttt{cur}(\texttt{app} \circ (\texttt{Id}_{T_\epsilon A} \times w))$$

. And hence, we have:

$$\texttt{cur}(f \circ (\texttt{Id} \times \sigma)) = (T_\epsilon A)^\sigma \circ \texttt{cur}(f)$$

And so:

$$
\begin{aligned}
\Delta' &= \texttt{app} \circ (([\texttt{cur}(\Delta_2' \circ \pi_2), \texttt{cur}(\Delta_3' \circ \pi_2)] \circ \Delta_1') \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By Definition} \\
&= \texttt{app} \circ (([\texttt{cur}(\Delta_2 \circ \sigma \circ \pi_2), \texttt{cur}(\Delta_3 \circ \sigma \circ \pi_2)] \circ \Delta_1') \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By Induction} \\
&= \texttt{app} \circ (([\texttt{cur}(\Delta_2 \circ \pi_2 \circ (\texttt{Id}_1 \times \sigma)), \texttt{cur}(\Delta_3 \circ \pi_2 \circ (\texttt{Id}_1 \times \sigma))] \circ \Delta_1 \circ \sigma) \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By product property} \\
&= \texttt{app} \circ (([(T_\epsilon A)^\sigma \circ \texttt{cur}(\Delta_2 \circ \pi_2), (T_\epsilon A)^\sigma \circ \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1 \circ \sigma) \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By } (T_\epsilon A)^\sigma \text{ property} \\
&= \texttt{app} \circ (((T_\epsilon A)^\sigma \circ [\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1 \circ \sigma) \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{Factor out transformation} \\
&= \texttt{app} \circ ((T_\epsilon A)^\sigma \times \texttt{Id}_{\Gamma'}) \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma'}) \circ (\sigma \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{Factor out Identity pairs} \\
&= \texttt{app} \circ (\texttt{Id}_{(T_\epsilon A)} \times \sigma) \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma'}) \circ (\sigma \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By defintion of } \texttt{app}, (T_\epsilon A)^\sigma \\
&= \texttt{app} \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma}) \circ (\sigma \times \sigma) \circ \delta_{\Gamma'} \quad \text{Push through pairs} \\
&= \texttt{app} \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma}) \circ \delta_{\Gamma} \circ \sigma \quad \text{By Definition of the diagonal morphism.} \\
&= \Delta \circ \sigma
\end{aligned}
$$

Case Bind: By inversion, we have Δ_1, Δ_2 such that:

$$
\Delta = (\text{Bind}) \frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v_1 \colon A} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma, x : A \vdash v_1 \colon B}}{\Phi \mid \Gamma \vdash \texttt{do}\ x \leftarrow v_1\ \texttt{in}\ v_2 : \texttt{M}_{\epsilon_1 \cdot \epsilon_2} B} \tag{7.18}
$$

By property **??**,

$$
\Phi \mid (\Gamma', x : A) \vdash (\sigma, x{:}= x \colon (\Gamma, x \colon A) \tag{7.19}
$$

With denotation (extension lemma)

$$
[\![\Phi \mid (\Gamma', x : A) \vdash (\sigma, x{:}= x \colon (\Gamma, x \colon A)]\!] = \sigma \times \texttt{Id}_A \tag{7.20}
$$

By induction, we derive Δ_1', Δ_2' such that:

$$
\begin{aligned}
\Delta_1' &= \Delta_1 \circ \sigma \\
\Delta_2' &= \Delta_2 \circ (\sigma \times \texttt{Id}_A) \quad \text{By Extension Lemma}
\end{aligned}
$$

And:

$$
\Delta' = (\text{Bind}) \frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v_1[\sigma] \colon A} \qquad \dfrac{\Delta_2'}{\Phi \mid \Gamma', x : A \vdash v_1[\sigma] \colon B}}{\Phi \mid \Gamma' \vdash (\texttt{do}\ x \leftarrow v_1\ \texttt{in}\ v_2\ )[\sigma] \colon \texttt{M}_{\epsilon_1 \cdot \epsilon_2} B} \tag{7.21}
$$

Hence:

$$
\begin{aligned}
\Delta' &= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1} \Delta_2' \circ \texttt{t}_{\epsilon_1, \Gamma', A} \circ \langle \texttt{Id}_{\Gamma'}, \Delta_1' \rangle \quad \text{By Definition} \\
&= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1}(\Delta_2 \circ (\sigma \times \texttt{Id}_A)) \circ \texttt{t}_{\epsilon_1, \Gamma', A} \circ \langle \texttt{Id}_{\Gamma'}, \Delta_1 \circ \sigma \rangle \quad \text{By Induction using the extension lemma} \\
&= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1}(\Delta_2) \circ \texttt{t}_{\epsilon_1, \Gamma, A} \circ (\sigma \times \texttt{Id}_{T_{\epsilon_1} A}) \circ \langle \texttt{Id}_{\Gamma'}, \Delta_1 \circ \sigma \rangle \quad \text{By Tensor Strength} \\
&= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1}(\Delta_2) \circ \texttt{t}_{\epsilon_1, \Gamma, A} \circ \langle \sigma, \Delta_1 \circ \sigma \rangle \quad \text{By Product rule} \\
&= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1}(\Delta_2) \circ \texttt{t}_{\epsilon_1, \Gamma, A} \circ \langle \texttt{Id}_{\Gamma}, \Delta_1 \rangle \circ \sigma \quad \text{By Product rule} \\
&= \Delta \circ \sigma \quad \text{By Defintion}
\end{aligned}
$$

Case Effect-Gen: By inversion, we have Δ_1 such that

$$\Delta = (\text{Effect-Gen})\frac{\dfrac{\Delta_1}{\Phi, \alpha \mid \Gamma \vdash v \colon A}}{\Phi \mid \Gamma \vdash \Lambda\alpha.v \colon \forall\epsilon.A} \tag{7.22}$$

By induction, we derive Δ_1' such that

$$\Delta' = (\text{Effect-Gen})\frac{\dfrac{\Delta_1'}{\Phi, \alpha \mid \Gamma' \vdash v[\sigma] \colon A}}{\Phi \mid \Gamma' \vdash (\Lambda\alpha.v)[\sigma] \colon \forall\epsilon.A} \tag{7.23}$$

Where

$$\begin{aligned}
\Delta_1' &= \Delta_1 \circ [\![\Phi, \alpha \mid \Gamma' \vdash \sigma \colon \Gamma]\!] \\
&= \Delta_1 \circ [\![\iota\pi \colon \Phi, a \triangleright \Phi]\!]^*(\sigma) \\
&= \Delta_1 \circ \pi_1^*(\sigma)
\end{aligned}$$

Hence

$$\begin{aligned}
\Delta \circ \sigma &= \overline{\Delta_1} \circ \sigma \\
&= \overline{\Delta_1 \circ \pi_1^*(\sigma)} \\
&= \overline{\Delta_1'} \\
&= \Delta'
\end{aligned}$$

Case Effect-Spec: By inversion, we derive Δ_1 such that

$$\Delta = (\text{Effect-Spec})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v \colon \forall\alpha.A} \quad \Phi\epsilon}{\Phi \mid \Gamma \vdash v\ \epsilon \colon A[\epsilon/\alpha]} \tag{7.24}$$

By induction, we derive Δ_1' such that

$$\Delta' = (\text{Effect-Spec})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v[\sigma] \colon \forall\alpha.A} \quad \Phi\epsilon}{\Phi \mid \Gamma' \vdash (v\ \epsilon)[\sigma] \colon A[\epsilon/\alpha]} \tag{7.25}$$

Where

$$\Delta_1' = \Delta \circ \sigma$$

Hence, if $h = [\![\Phi \vdash \epsilon \colon \texttt{Effect}]\!]$

$$\begin{aligned}
\Delta \circ \sigma &= \langle \texttt{Id}_I, h\rangle^*(\epsilon[\![\Phi, \beta \vdash A[\alpha/\beta] \colon \texttt{Effect}]\!]) \circ \Delta_1 \circ \sigma \\
&= \langle \texttt{Id}_I, h\rangle^*(\epsilon[\![\Phi, \beta \vdash A[\alpha/\beta] \colon \texttt{Effect}]\!]) \circ \Delta_1' \\
&= \Delta'
\end{aligned}$$

Chapter 8

Term-Environment Weakening Theorem

Theorem 8.0.1 (Term-Environment Weakening). *If* $w = [\![\Phi \vdash \omega \colon \Gamma' \triangleright G]\!]$ *and* Δ *derives* $\Phi \mid \Gamma \vdash v \colon A$ *then there exists* Δ' *deriving* $\Phi \mid \Gamma' \vdash v \colon A$ *such that* $\Delta' = \Delta \circ \omega$

Proof: We induct over the structure of typing derivations of $\Phi \mid \Gamma \vdash v \colon A$, assuming $\Phi \vdash \omega \colon \Gamma' \triangleright \Gamma$ holds. In each case, we construct the new derivation Δ' from the derivation Δ giving $\Phi \mid \Gamma \vdash v \colon A$ and show that $\Delta \circ [\![\Phi \vdash \omega \colon \Gamma' \triangleright \Gamma]\!] = \Delta'$

Case Varand Weaken: We case split on the weakening ω.

Case: $\omega = \iota$ Then $\Gamma' = \Gamma$, and so $\Phi \mid \Gamma' \vdash x \colon A$ holds and the derivation Δ' is the same as Δ

$$\Delta' = \Delta = \Delta \circ \mathtt{Id}_{\Gamma} = \Delta \circ [\![\Phi \vdash \iota \colon \Gamma \triangleright \Gamma]\!] \tag{8.1}$$

Case: $\omega = \omega' \pi$ Then $\Gamma' = (\Gamma'', x' : A')$ and $\Phi \vdash \omega' \colon \Gamma'' \triangleright \Gamma$. So by induction, there is a tree, Δ_1 deriving $\Phi \mid \Gamma'' \vdash x \colon A$, such that

$$\Delta_1 = \Delta \circ [\![\Phi \vdash \omega' \colon \Gamma'' \triangleright \Gamma]\!] \quad \text{By Induction} \tag{8.2}$$

, and hence by the weaken rule, we have

$$(\text{Weaken})\frac{\Phi \mid \Gamma'' \vdash x \colon A}{\Phi \mid \Gamma'', x' : A' \vdash x \colon A} \tag{8.3}$$

This preserves denotations:

$$\begin{aligned} \Delta' &= \Delta_1 \circ \pi_1 \quad \text{By Definition} \\ &= \Delta \circ [\![\Phi \vdash \omega' \colon \Gamma'' \triangleright \Gamma]\!] \circ \pi_1 \quad \text{By induction} \\ &= \Delta \circ [\![\Phi \vdash \omega' \pi_1 \colon \Gamma' \triangleright \Gamma]\!] \quad \text{By denotation of weakening} \end{aligned}$$

Case: $\omega = \omega' \times$ Then

$$\Gamma' = \Gamma''', x' : B$$
$$\Gamma = \Gamma'', x' : A'$$
$$B \leq:_\Phi A$$

Case: $x = x'$ Then $A = A'$.

Then we derive the new derivation, Δ' as so:

$$(\text{Subtype})\frac{(\text{Var})\dfrac{\Phi \vdash \Gamma \ \texttt{Ok}}{\Phi \mid \Gamma''', x : B \vdash x \colon B} \qquad B \leq:_\Phi A}{\Phi \mid \Gamma' \vdash x \colon A} \tag{8.4}$$

This preserves denotations:

$$\begin{aligned}\Delta' &= [\![B \leq:_\Phi A]\!] \circ \pi_2 \quad \text{By Definition}\\ &= \pi_2 \circ ([\![\Phi \vdash \omega' \colon \Gamma''' \triangleright \Gamma'']\!] \times [\![B \leq:_\Phi A]\!]) \quad \text{By the properties of binary products}\\ &= \Delta \circ [\![\Phi \vdash \omega \colon \Gamma' \triangleright \Gamma]\!] \quad \text{By Definition}\end{aligned}$$

Case: $x \neq x'$ Then

$$\Delta = (\text{Weaken})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma'' \vdash x \colon A}}{\Phi \mid \Gamma \vdash x \colon A} \tag{8.5}$$

By induction with $\Phi \vdash \omega \colon \Gamma''' \triangleright \Gamma''$, we have a derivation Δ_1 of $\Phi \mid \Gamma''' \vdash x \colon A$

We have the weakened derivation:

$$\Delta' = (\text{Weaken})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma''' \vdash x \colon A}}{\Phi \mid \Gamma' \vdash x \colon A} \tag{8.6}$$

This preserves denotations:

By induction, we have
$$\Delta_1' = \Delta_1 \circ [\![\Phi \vdash \omega \colon \Gamma''' \triangleright \Gamma'']\!] \tag{8.7}$$

So we have:

$$\begin{aligned}\Delta' &= \Delta_1' \circ \pi_1 \quad \text{By denotation definition}\\ &= \Delta_1 \circ [\![\Phi \vdash \omega' \colon \Gamma''' \triangleright \Gamma'']\!] \quad \text{By induction} \circ \pi_1\\ &= \Delta_1 \circ \pi_1 \circ ([\![\Phi \vdash \omega' \colon \Gamma''' \triangleright \Gamma'']\!] \times [\![A' \leq:_\Phi B]\!]) \quad \text{By product properties}\\ &= \Delta \circ [\![\Phi \vdash \omega \colon \Gamma' \triangleright \Gamma]\!] \quad \text{By definition}\end{aligned}$$

From this point onwards, since we no-longer case split over the weakening relations, we write the denotation $[\![\Phi \vdash \omega \colon \Gamma' \triangleright \Gamma']\!]$, simply as ω.

Case Const: The constant typing rules, `()`, `true`, `false`, $\mathtt{k}^{A}$, all proceed by the same logic. Hence I shall only prove the theorems for the case $\mathtt{k}^{A}$.

$$(\text{Const})\frac{\Phi \vdash \Gamma\ \ \mathtt{Ok}}{\Phi \mid \Gamma \vdash \mathtt{k}^{A} \colon A} \tag{8.8}$$

By inversion, we have $\Phi \vdash \Gamma\ \ \mathtt{Ok}$, so we have $\Phi \vdash \Gamma'\ \ \mathtt{Ok}$.

Hence

$$(\text{Const})\frac{\Phi \vdash \Gamma'\ \ \mathtt{Ok}}{\Phi \mid \Gamma' \vdash \mathtt{k}^{A} \colon A} \tag{8.9}$$

Holds.

This preserves denotations:

$$\begin{aligned} \Delta' &= [\![\mathtt{k}^{A}]\!] \circ \langle\rangle_{\Gamma'} && \text{By definition} \\ &= [\![\mathtt{k}^{A}]\!] \circ \langle\rangle_{\Gamma} \circ \omega && \text{By the terminal property} \\ &= \Delta && \text{By Definition} \end{aligned}$$

Case Fn: By inversion, we have a derivation Δ_1 giving

$$\Delta = (\text{Fn})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma, x \colon A \vdash v \colon B}}{\Phi \mid \Gamma \vdash \lambda x \colon A.v : A \to B} \tag{8.10}$$

Since $\Phi \vdash \omega \colon \Gamma' \triangleright \Gamma$, we have:

$$\Phi \vdash \omega\times \colon (\Gamma, x : A) \triangleright (\Gamma, x \colon A) \tag{8.11}$$

Hence, by induction, using $\Phi \vdash \omega\times \colon (\Gamma, x : A) \triangleright (\Gamma, x \colon A)$, we derive Δ_1':

$$\Delta' = (\text{Fn})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma', x : A \vdash v \colon B}}{\Phi \mid \Gamma', x : A \vdash \lambda x \colon A.v : A \to B} \tag{8.12}$$

This preserves denotations:

$$\begin{aligned} \Delta' &= \mathtt{cur}(\Delta_1') && \text{By Definition} \\ &= \mathtt{cur}(\Delta_1 \circ (\omega \times \mathtt{Id}_{\Gamma})) && \text{By the denotation of } \omega\times \\ &= \mathtt{cur}(\Delta_1) \circ \omega && \text{By the exponential property} \\ &= \Delta \circ \omega && \text{By Definition} \end{aligned}$$

Case Subtype:

$$(\text{Subtype})\frac{\Phi \mid \Gamma \vdash v\colon A \qquad A {\leq:}_{\Phi} B}{\Phi \mid \Gamma \vdash v\colon B} \tag{8.13}$$

by inversion, we have a derivation Δ_1

$$\frac{\Delta_1}{\Phi \mid \Gamma \vdash v\colon A} \tag{8.14}$$

So by induction, we have a derivation Δ_1' such that:

$$(\text{Subtype})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v\colon a} \qquad A {\leq:}_{\Phi} B}{\Phi \mid \Gamma' \vdash v\colon B} \tag{8.15}$$

This preserves denotations:

$$\begin{aligned}
\Delta' &= [\![A {\leq:}_{\Phi} B]\!] \circ \Delta_1' \quad \text{By Definition}\\
&= [\![A {\leq:}_{\Phi} B]\!] \circ \Delta_1 \circ \omega \quad \text{By induction}\\
&= \Delta \circ \omega \quad \text{By Definition}
\end{aligned}$$

Case Return: We have the Subderivation Δ_1 such that

$$\Delta = (\text{Return})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v\colon A}}{\Phi \mid \Gamma \vdash \texttt{return}\ v : \texttt{M}_{\texttt{1}} A} \tag{8.16}$$

Hence, by induction, with $\Phi \vdash \omega\colon \Gamma' \triangleright \Gamma$, we find the derivation Δ_1' such that:

$$\Delta' = (\text{Return})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v\colon A}}{\Phi \mid \Gamma' \vdash \texttt{return}\ v : \texttt{M}_{\texttt{1}} A} \tag{8.17}$$

This preserves denotations:

$$\begin{aligned}
\Delta' &= \eta_A \circ \Delta_1' \quad \text{By definition}\\
&= \eta_A \circ \Delta_1 \circ \omega \quad \text{By induction of } \Delta_1, \Delta_1'\\
&= \Delta \circ \omega \quad \text{By Definition}
\end{aligned}$$

Case Apply: By inversion, we have derivations Δ_1, Δ_2 such that

$$\Delta = (\text{Apply})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v_1\colon A \to B} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma \vdash v_2\colon A}}{\Phi \mid \Gamma \vdash v_1\ v_2\colon B} \tag{8.18}$$

By induction, this gives us the respective derivations: Δ_1', Δ_2' such that

$$\Delta' = (\text{Apply})\dfrac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v_1 \colon A \to B} \qquad \dfrac{\Delta_2'}{\Phi \mid \Gamma' \vdash v_2 \colon A}}{\Phi \mid \Gamma' \vdash v_1\ v_2 \colon B} \tag{8.19}$$

This preserves denotations:

$$\begin{aligned}
\Delta' &= \mathsf{app} \circ \langle \Delta_1', \Delta_2' \rangle \quad \text{By Definition} \\
&= \mathsf{app} \circ \langle \Delta_1 \circ \omega, \Delta_2 \circ \omega \rangle \quad \text{By induction on } \Delta_1, \Delta_2 \\
&= \mathsf{app} \circ \langle \Delta_1, \Delta_2 \rangle \circ \omega \\
&= \Delta \circ \omega \quad \text{By Definition}
\end{aligned}$$

Case If: By inversion, we have the Subderivations $\Delta_1, \Delta_2, \Delta_3$, such that:

$$\Delta = (\text{If})\dfrac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v \colon \texttt{Bool}} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma \vdash v_1 \colon A} \qquad \dfrac{\Delta_3}{\Phi \mid \Gamma \vdash v_2 \colon A}}{\Phi \mid \Gamma \vdash \texttt{if}_A\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2 : A} \tag{8.20}$$

By induction, this gives us the Subderivations $\Delta_1', \Delta_2', \Delta_3'$ such that

$$\Delta' = (\text{If})\dfrac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v \colon \texttt{Bool}} \qquad \dfrac{\Delta_2'}{\Phi \mid \Gamma' \vdash v_1 \colon A} \qquad \dfrac{\Delta_3'}{\Phi \mid \Gamma' \vdash v_2 \colon A}}{\Phi \mid \Gamma' \vdash \texttt{if}_A\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2 : A} \tag{8.21}$$

And

$$\begin{aligned}
\Delta_1' &= \Delta_1 \circ \omega \\
\Delta_3' &= \Delta_2 \circ \omega \\
\Delta_3' &= \Delta_3 \circ \omega
\end{aligned}$$

This preserves denotations. Since $\omega : \Gamma' \to \Gamma$,
Let $(T_\epsilon A)^\omega : T_\epsilon A^\Gamma \to T_\epsilon A^{\Gamma'}$ be as defined in ExSh 3 ([1]) That is:

$$(T_\epsilon A)^\omega = \texttt{cur}(\mathsf{app} \circ (\texttt{Id}_{T_\epsilon A} \times w))$$

. And hence, we have:

$$\texttt{cur}(f \circ (\texttt{Id} \times \omega)) = (T_\epsilon A)^\omega \circ \texttt{cur}(f)$$

$$\begin{aligned}
\Delta' &= \mathsf{app} \circ (([\texttt{cur}(\Delta_2' \circ \pi_2), \texttt{cur}(\Delta_3' \circ \pi_2)] \circ \Delta_1') \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By Definition} \\
&= \mathsf{app} \circ (([\texttt{cur}(\Delta_2 \circ \omega \circ \pi_2), \texttt{cur}(\Delta_3 \circ \omega \circ \pi_2)] \circ \Delta_1') \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By Induction} \\
&= \mathsf{app} \circ (([\texttt{cur}(\Delta_2 \circ \pi_2 \circ (\texttt{Id}_1 \times \omega)), \texttt{cur}(\Delta_3 \circ \pi_2 \circ (\texttt{Id}_1 \times \omega))] \circ \Delta_1 \circ \omega) \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By product property} \\
&= \mathsf{app} \circ (([(T_\epsilon A)^\omega \circ \texttt{cur}(\Delta_2 \circ \pi_2), (T_\epsilon A)^\omega \circ \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1 \circ \omega) \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By } (T_\epsilon A)^\omega \text{ property} \\
&= \mathsf{app} \circ (((T_\epsilon A)^\omega \circ [\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1 \circ \omega) \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{Factor out transformation} \\
&= \mathsf{app} \circ ((T_\epsilon A)^\omega \times \texttt{Id}_{\Gamma'}) \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma'}) \circ (\omega \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{Factor out Identity pairs} \\
&= \mathsf{app} \circ (\texttt{Id}_{(T_\epsilon A)} \times \omega) \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma'}) \circ (\omega \times \texttt{Id}_{\Gamma'}) \circ \delta_{\Gamma'} \quad \text{By defintion of } \mathsf{app}, (T_\epsilon A)^\omega \\
&= \mathsf{app} \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma}) \circ (\omega \times \omega) \circ \delta_{\Gamma'} \quad \text{Push through pairs} \\
&= \mathsf{app} \circ (([\texttt{cur}(\Delta_2 \circ \pi_2), \texttt{cur}(\Delta_3 \circ \pi_2)] \circ \Delta_1) \times \texttt{Id}_{\Gamma}) \circ \delta_{\Gamma} \circ \omega \quad \text{By Definition of the diagonal morphism.} \\
&= \Delta \circ \omega
\end{aligned}$$

Case Bind: By inversion, we have derivations Δ_1, Δ_2 such that:

$$\Delta = (\text{Bind})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v_1 \colon \mathtt{M}_{\mathbb{E}_1} A} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma, x : A \vdash v_2 \colon \mathtt{M}_{\epsilon_2} B}}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B} \tag{8.22}$$

If $\Phi \vdash \omega \colon \Gamma' \triangleright \Gamma$ then $\Phi \vdash \omega \times \colon \Gamma', x : A \triangleright \Gamma, x \colon A$, so by induction, we can derive Δ_1', Δ_2' such that:

$$\Delta' = (\text{Bind})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v_1 \colon \mathtt{M}_{\epsilon_1} A} \qquad \dfrac{\Delta_2'}{\Phi \mid \Gamma', x : A \vdash v_2 \colon \mathtt{M}_{\epsilon_2} B}}{\Phi \mid \Gamma' \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B} \tag{8.23}$$

This preserves denotations:

$$\begin{aligned}
\Delta' &= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1} \Delta_2' \circ \mathtt{t}_{\epsilon_1, \Gamma', A} \circ \langle \mathtt{Id}_{G'}, \Delta_1' \rangle \quad \text{By definition} \\
&= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1} (\Delta_2 \circ (\omega \times \mathtt{Id}_A)) \circ \mathtt{t}_{\epsilon_1, \Gamma', A} \circ \langle \mathtt{Id}_{G'}, \Delta_1 \circ \omega \rangle \quad \text{By induction on } \Delta_1', \Delta_2' \\
&= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1} \Delta_2 \circ \mathtt{t}_{\epsilon_1, \Gamma, A} \circ \langle \omega, \Delta_1 \circ \omega \rangle \quad \text{By tensor strength} \\
&= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1} \Delta_2 \circ \mathtt{t}_{\epsilon_1, \Gamma, A} \circ \langle \mathtt{Id}_\Gamma, \Delta_1 \rangle \circ \omega \quad \text{By product property} \\
&= \Delta \quad \text{By definition}
\end{aligned}$$

Case Effect-Gen: By inversion, we have Δ_1 such that

$$\Delta = (\text{Effect-Gen})\frac{\dfrac{\Delta_1}{\Phi, \alpha \mid \Gamma \vdash v \colon A}}{\Phi \mid \Gamma \vdash \Lambda \alpha . v \colon \forall \epsilon . A} \tag{8.24}$$

By induction, we derive Δ_1' such that

$$\Delta' = (\text{Effect-Gen})\frac{\dfrac{\Delta_1'}{\Phi, \alpha \mid \Gamma' \vdash v \colon A}}{\Phi \mid \Gamma' \vdash (\Lambda \alpha . v) \colon \forall \epsilon . A} \tag{8.25}$$

Where

$$\begin{aligned}
\Delta_1' &= \Delta_1 \circ [\![\Phi, \alpha \vdash \omega \colon \Gamma' \triangleright \Gamma]\!] \\
&= \Delta_1 \circ [\![\iota\pi \colon \Phi, a \triangleright \Phi]\!]^*(\omega) \\
&= \Delta_1 \circ \pi_1^*(\omega)
\end{aligned}$$

Hence

$$\begin{aligned}
\Delta \circ \omega &= \overline{\Delta_1} \circ \omega \\
&= \overline{\Delta_1 \circ \pi_1^*(\omega)} \\
&= \overline{\Delta_1'} \\
&= \Delta'
\end{aligned}$$

Case Effect-Spec: By inversion, we derive Δ_1 such that

$$\Delta = (\text{Effect-Spec})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v\colon \forall\alpha.A} \qquad \Phi\epsilon}{\Phi \mid \Gamma \vdash v\ \epsilon\colon A[\epsilon/\alpha]} \tag{8.26}$$

By induction, we derive Δ_1' such that

$$\Delta' = (\text{Effect-Spec})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma' \vdash v\colon \forall\alpha.A} \qquad \Phi\epsilon}{\Phi \mid \Gamma' \vdash v\ \epsilon\colon A[\epsilon/\alpha]} \tag{8.27}$$

Where

$$\Delta_1' = \Delta \circ \omega$$

Hence, if $h = [\![\Phi \vdash \epsilon\colon \texttt{Effect}]\!]$

$$\begin{aligned}\Delta \circ \omega &= \langle \texttt{Id}_I, h\rangle^*(\epsilon[\![\Phi, \beta \vdash A[\alpha/\beta]\colon \texttt{Effect}]\!]) \circ \Delta_1 \circ \omega \\ &= \langle \texttt{Id}_I, h\rangle^*(\epsilon[\![\Phi, \beta \vdash A[\alpha/\beta]\colon \texttt{Effect}]\!]) \circ \Delta_1' \\ &= \Delta'\end{aligned}$$

Chapter 9

Unique Denotation Theorem

9.1 Reduced Type Derivation

A reduced type derivation is one where subtype and subeffect rules must, and may only, occur at the root or directly above an *(If)*, or **(Apply)** rule.

In this section, I shall prove that there is at most one reduced derivation of $\Phi \mid \Gamma \vdash v\colon A$. Secondly, I shall present a function for generating reduced derivations from arbitrary typing derivations, in a way that does not change the denotations. These imply that all typing derivations of a type-relation have the same denotation.

9.2 Reduced Type Derivations are Unique

Theorem 9.2.1 (Reduced Type Derivations are Unique)**.** *For each instance of the relation $\Phi \mid \Gamma \vdash v\colon A$,there exists at most one reduced derivation of $\Phi \mid \Gamma \vdash v\colon A$.*

Proof: This is proved by induction over the typing rules on the bottom rule used in each derivation.

Case Variables: To find the unique derivation of $\Phi \mid \Gamma \vdash x\colon A$, we case split on the term-environment, Γ.

Case: $\Gamma = \Gamma', x : A'$ Then the unique reduced derivation of $\Phi \mid \Gamma \vdash x\colon A$ is, if $A' \leq:_\Phi A$, as below:

$$\text{(Subtype)}\frac{\text{(Var)}\dfrac{\Phi \vdash \Gamma', x : A' \ \texttt{Ok}}{\Phi \mid \Gamma, x : A' \vdash x\colon A'} \qquad A' \leq:_\Phi A}{\Phi \mid \Gamma', x : A' \vdash x\colon A} \tag{9.1}$$

Case: $\Gamma = \Gamma', y : B$ with $y \neq x$.

Hence, if $\Phi \mid \Gamma \vdash x\colon A$ holds, then so must $\Phi \mid \Gamma' \vdash x\colon A$.

Let

$$\text{(Subtype)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma' \vdash x\colon A'} \qquad A' \leq: A}{\Phi \mid \Gamma' \vdash x\colon A} \tag{9.2}$$

Be the unique reduced derivation of $\Phi \mid \Gamma' \vdash x\colon A$.

Then the unique reduced derivation of $\Phi \mid \Gamma \vdash x\colon A$ is:

$$\text{(Subtype)}\dfrac{\text{(Weaken)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma, x : A' \vdash x\colon A'}}{\Phi \mid \Gamma \vdash x\colon A'} \qquad A' \leq:_{\Phi} A}{\Phi \mid \Gamma \vdash x\colon A} \tag{9.3}$$

Case Const: For each of the constants, ($\mathtt{k}^{A}$, `true`, `false`, `()`), there is exactly one possible derivation for $\Phi \mid \Gamma \vdash c\colon A$ for a given A. I shall give examples using the case $\mathtt{k}^{A}$

$$\text{(Subtype)}\dfrac{\text{(Const)}\dfrac{\Gamma\ \mathtt{Ok}}{\Gamma \vdash \mathtt{k}^{A}\colon A} \qquad A \leq:_{\Phi} B}{\Phi \mid \Gamma \vdash \mathtt{k}^{A}\colon B}$$

If $A = B$, then the subtype relation is the identity subtype ($A \leq:_{\Phi} A$).

Case Fn: The reduced derivation of $\Phi \mid \Gamma \vdash \lambda x\colon A.v : A' \to B'$ is:

$$\text{(Subtype)}\dfrac{\text{(Fn)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma, x\colon A \vdash v\colon B}}{\Phi \mid \Gamma \vdash \lambda x\colon A.B : A \to B} \qquad A \to B \leq:_{\Phi} A' \to B'}{\Phi \mid \Gamma \vdash \lambda x\colon A.v : A' \to B'}$$

Where

$$\text{(Subtype)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma, x\colon A \vdash v\colon B} \qquad B \leq:_{\Phi} B'}{\Phi \mid \Gamma, x\colon A \vdash v\colon B'} \tag{9.4}$$

is the reduced derivation of $\Phi \mid \Gamma, x\colon A \vdash v\colon B$ if it exists.

Case Return: The reduced denotation of $\Phi \mid \Gamma \vdash \mathtt{return}\ v : B$ is

$$\text{(Subtype)}\dfrac{\text{(Return)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v\colon A}}{\Phi \mid \Gamma \vdash \mathtt{return}\ v : \mathtt{M}_{1} A} \qquad \text{(T-Effect)}\dfrac{1 \leq_{\Phi} \epsilon \qquad A \leq:_{\Phi} B}{\mathtt{M}_{1} A \leq:_{\Phi} \mathtt{M}_{\epsilon} B}}{\Phi \mid \Gamma \vdash \mathtt{return}\ v : \mathtt{M}_{\epsilon} B}$$

Where

$$\text{(Subtype)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v\colon A} \qquad A \leq: B}{\Phi \mid \Gamma \vdash v\colon B}$$

is the reduced derivation of $\Phi \mid \Gamma \vdash v\colon B$

Case Apply: If

$$\text{(Subtype)}\frac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v_1 \colon A \to B} \qquad A \to B \leq: A' \to B'}{\Phi \mid \Gamma \vdash v_1 \colon A' \to B'}$$

and

$$\text{(Subtype)}\frac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v_2 \colon A''} \qquad A'' \leq: A'}{\Phi \mid \Gamma \vdash v_2 \colon A'}$$

Are the reduced type derivations of $\Phi \mid \Gamma \vdash v_1 \colon A' \to B'$ and $\Phi \mid \Gamma \vdash v_2 \colon A'$

Then we can construct the reduced derivation of $\Phi \mid \Gamma \vdash v_1\ v_2 \colon B$ as

$$\text{(Subtype)}\frac{\text{(Apply)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v_1 \colon A \to B} \qquad \text{(Subtype)}\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v \colon A''} \qquad A'' \leq:_\Phi A}{\Phi \mid \Gamma \vdash v \colon A}}{\Phi \mid \Gamma \vdash v_1\ v_2 \colon B} \qquad B \leq:_\Phi B'}{\Phi \mid \Gamma \vdash v_1\ v_2 \colon B'}$$

Case If: Let

$$\text{(Subtype)}\frac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v \colon B'} \qquad B' \leq: \mathtt{Bool}}{\Phi \mid \Gamma \vdash v \colon \mathtt{Bool}} \tag{9.5}$$

$$\text{(Subtype)}\frac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v_1 \colon A'} \qquad A' \leq: A}{\Phi \mid \Gamma \vdash v_1 \colon A} \tag{9.6}$$

$$\text{(Subtype)}\frac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v_2 \colon A''} \qquad A'' \leq: A}{\Phi \mid \Gamma \vdash v_2 \colon A} \tag{9.7}$$

Be the unique reduced reduced derivations of $\Phi \mid \Gamma \vdash v \colon \mathtt{Bool}$, $\Phi \mid \Gamma \vdash v_1 \colon A$, $\Phi \mid \Gamma \vdash v_2 \colon A$.

Then the only reduced derivation of $\Phi \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : B$ is:

$$\text{(Subtype)}\frac{\text{(If)}\dfrac{\text{(Subtype)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v \colon B'} \quad B' \leq: \mathtt{Bool}}{\Phi \mid \Gamma \vdash v \colon \mathtt{Bool}} \quad \text{(Subtype)}\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v_1 \colon A'} \quad A' \leq: A}{\Phi \mid \Gamma \vdash v_1 \colon A} \quad \text{(Subtype)}\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v_2 \colon A''} \quad A'' \leq: A}{\Phi \mid \Gamma \vdash v_2 \colon A}}{\Phi \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : A} \qquad A \leq:_\Phi B}{\Phi \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : B} \tag{9.8}$$

Case Bind: This case makes use of the weakening theorem on term environments. Let the trees in equations **??**, **??** be the respective unique reduced type derivations of the subterms. By weakening, $\Phi \vdash \iota \times \colon (\Gamma, x : A) \triangleright (\Gamma, x : A')$ so if there's a derivation of $\Phi \mid (\Gamma, x : A') \vdash v_2 \colon B$, there's also one of $\Phi \mid \Gamma, x \colon A \vdash v_2 \colon B$ (equation **??**).

$$\text{(Subtype)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v_1 : \mathtt{M}_{\epsilon_1} A} \qquad \text{(T-Effect)}\dfrac{A \leq:_\Phi A' \qquad \epsilon_1 \leq_\Phi \epsilon_1'}{\mathtt{M}_{\epsilon_1} A \leq:_\Phi \mathtt{M}_{\epsilon_1'} A'}}{\Phi \mid \Gamma \vdash v_1 : \mathtt{M}_{\epsilon_1'} A'} \tag{9.9}$$

$$\text{(Subtype)}\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma, x : A' \vdash v_2 : \mathtt{M}_{\epsilon_2} B} \qquad \text{(T-Effect)}\dfrac{B \leq:_\Phi B' \qquad \epsilon_2 \leq_\Phi \epsilon_2'}{\mathtt{M}_{\epsilon_2} B \leq:_\Phi \mathtt{M}_{\epsilon_2'} B'}}{\Phi \mid \Gamma, x : A' \vdash v_2 : \mathtt{M}_{\epsilon_2'} B'} \tag{9.10}$$

$$\text{(Subtype)}\dfrac{\dfrac{\Delta''}{\Phi \mid (\Gamma, x : A) \vdash v_2 : \mathtt{M}_{\epsilon_2} B} \qquad \text{(T-Effect)}\dfrac{B \leq:_\Phi B' \qquad \epsilon_2 \leq_\Phi \epsilon_2'}{\mathtt{M}_{\epsilon_2} B \leq:_\Phi \mathtt{M}_{\epsilon_2'} B'}}{\Phi \mid (\Gamma, x : A) \vdash v_2 : \mathtt{M}_{\epsilon_2'} B'} \tag{9.11}$$

Since the effects monoid operation is monotone, if $\epsilon_1 \leq_\Phi \epsilon_1'$ and $\epsilon_2 \leq_\Phi \epsilon_2'$ then $\epsilon_1 \cdot \epsilon_2 \leq_\Phi \epsilon_1' \cdot \epsilon_2'$. Hence the reduced type derivation of $\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1' \cdot \epsilon_2'} B'$ can be seen in equation **??**.

$$\text{(Subtype)}\dfrac{\text{(Bind)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v_1 : \mathtt{M}_{\epsilon_1} A} \qquad \dfrac{\Delta''}{\Phi \mid \Gamma, x : A \vdash v_2 : \mathtt{M}_{\epsilon_2} B}}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B} \qquad \text{(T-Effect)}\dfrac{\epsilon_1 \cdot \epsilon_2 \leq_\Phi \epsilon_1' \cdot \epsilon_2' \qquad B \leq:_\Phi B'}{\mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B \leq:_\Phi \mathtt{M}_{\epsilon_1' \cdot \epsilon_2'} B'}}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1' \cdot \epsilon_2'} B'} \tag{9.12}$$

Case Effect-Gen: The unique reduced derivation of $\Phi \mid \Gamma \vdash \Lambda\alpha.A : \forall\alpha.B$ is

$$\text{(Subtype)}\dfrac{\text{(Effect-Gen)}\dfrac{\dfrac{\Delta}{\Phi, \alpha \mid \Gamma \vdash v : A}}{\Phi \mid \Gamma \vdash \Lambda\alpha.v : \forall\alpha.A} \qquad \forall\alpha.A \leq_\Phi \forall\alpha.B}{\Phi \mid \Gamma \vdash \Lambda\alpha.B : \forall\alpha.B} \tag{9.13}$$

Where

$$\text{(Subtype)}\dfrac{\dfrac{\Delta}{\Phi, \alpha \mid \Gamma \vdash v : A} \qquad A \leq:_{\Phi,\alpha} B}{\Phi, \alpha \mid \Gamma \vdash v : B} \tag{9.14}$$

Is the unique reduced derivation of $\Phi, \alpha \mid \Gamma \vdash v : B$

Case Effect-Spec: The unique reduced derivation of $\Phi \mid \Gamma \vdash v\ \alpha : B'$ is

$$\text{(Subtype)}\dfrac{\text{(Effect-Spec)}\dfrac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v : \forall\alpha.A} \qquad \Phi\epsilon}{\Phi \mid \Gamma \vdash v\ \epsilon : A[\epsilon/\alpha]} \qquad A[\epsilon/\alpha] \leq:_\Phi B'}{\Phi \mid \Gamma \vdash v\ \alpha : B'} \tag{9.15}$$

Where $B[\epsilon/\alpha] \leq:_\Phi B'$ and

$$\text{(Subtype)}\frac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v\colon \forall\alpha.B} \qquad \text{(S-Quantification)}\dfrac{A \leq:_{\Phi,\alpha} B}{\forall\alpha.A \leq:_\Phi \forall\alpha.B}}{\Phi \mid \Gamma \vdash v\colon \forall\alpha.B} \tag{9.16}$$

9.3 Each type derivation has a reduced equivalent with the same denotation.

We introduce a function, *reduce* that maps each valid type derivation of $\Phi \mid \Gamma \vdash v\colon A$ to a reduced equivalent with the same denotation. To do this, we do case analysis over the root type rule of a derivation and prove that the denotation is not changed.

Theorem 9.3.1 (Reduction Function)**.** *There exists a function reduce that maps each typing derivation to a reduced derivation of the same term and type and the same denotation.*

Proof:

Case Constants: For the constants `true`, `false`, $\mathtt{k}^A$, etc, *reduce* simply returns the derivation, as it is already reduced. This trivially preserves the denotation.

$$reduce(\text{(Const)}\frac{\Gamma\ \mathtt{Ok}}{\Gamma \vdash \mathtt{k}^A\colon A}) = \text{(Const)}\frac{\Gamma\ \mathtt{Ok}}{\Gamma \vdash \mathtt{k}^A\colon A}$$

Case Var:

$$reduce(\text{(Var)}\frac{\Phi \vdash \Gamma\ \mathtt{Ok}}{\Phi \mid \Gamma, x\colon A \vdash x\colon A}) = \text{(Var)}\frac{\Phi \vdash \Gamma\ \mathtt{Ok}}{\Phi \mid \Gamma, x\colon A \vdash x\colon A} \tag{9.17}$$

Preserves denotation trivially.

Case Weaken:

reduce **definition** To find:

$$reduce(\text{(Weaken)}\frac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash x\colon A}}{\Phi \mid \Gamma, y\colon B \vdash x\colon A}) \tag{9.18}$$

Let

$$\text{(Subtype)}\frac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash x\colon A} \qquad A' \leq:_\Phi A}{\Phi \mid \Gamma \vdash x\colon A} = reduce(\Delta) \tag{9.19}$$

In

$$(\text{Subtype})\frac{(\text{Weaken})\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash x \colon A'}}{\Phi \mid \Gamma, y \colon B \vdash x \colon A'} \qquad A' \leq:_{\Phi} A}{\Phi \mid \Gamma, y \colon B \vdash x \colon A} \tag{9.20}$$

Preserves Denotation Using the construction of denotations, we can find the denotation of the original derivation to be:

$$[\![(\text{Weaken})\frac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash x \colon A}}{\Phi \mid \Gamma, y \colon B \vdash x \colon A}]\!] = \Delta \circ \pi_1 \tag{9.21}$$

Similarly, the denotation of the reduced denotation is:

$$[\![(\text{Subtype})\frac{(\text{Weaken})\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash x \colon A'}}{\Phi \mid \Gamma, y \colon B \vdash x \colon A'} \qquad A' \leq:_{\Phi} A}{\Phi \mid \Gamma, y \colon B \vdash x \colon A}]\!] = [\![A' \leq:_{\Phi} A]\!] \circ \Delta' \circ \pi_1 \tag{9.22}$$

By induction on *reduce* preserving denotations and the reduction of Δ (**??**), we have:

$$\Delta = [\![A' \leq:_{\Phi} A]\!] \circ \Delta' \tag{9.23}$$

So the denotations of the un-reduced and reduced derivations are equal.

Case Fn:

reduce **definition** To find:

$$reduce((\text{Fn})\frac{\dfrac{\Delta}{\Phi \mid \Gamma, x \colon A \vdash v \colon B}}{\Phi \mid \Gamma \vdash \lambda x \colon A.v : A \to B}) \tag{9.24}$$

Let

$$(\text{Subtype})\frac{\dfrac{\Delta'}{\Phi \mid \Gamma, x \colon A \vdash v \colon B'} B' \leq:_{\Phi} B \qquad \Phi \mid \Gamma, x \colon A \vdash v \colon \mathtt{M}_{\epsilon_2} B}{=} reduce(\Delta) \tag{9.25}$$

In

$$(\text{Subtype})\frac{(\text{Fn})\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma, x \colon A \vdash v \colon B'}}{\Phi \mid \Gamma \vdash \lambda x \colon A.v : A \to B'} \qquad A \to B' \leq:_{\Phi} A \to B}{\Phi \mid \Gamma \vdash \lambda x \colon A.v : A \to B} \tag{9.26}$$

Preserves Denotation Let

$$f = [\![B' \leq:_\Phi B']\!]$$
$$[\![A \to B' \leq:_\Phi A \to B]\!] = f^A = \mathtt{cur}(f \circ \mathtt{app})$$

Then

$$\begin{aligned} \mathit{before} &= \mathtt{cur}(\Delta) \quad \text{By definition} \\ &= \mathtt{cur}(f \circ \Delta') \quad \text{By reduction of } \Delta \\ &= f^A \circ \mathtt{cur}(\Delta') \quad \text{By the property of } f^X \circ \mathtt{cur}(g) = \mathtt{cur}(f \circ g) \\ &= \mathit{after} \quad \text{By definition} \end{aligned}$$

Case Subtype:

reduce **definition** To find:

$$\mathit{reduce}((\text{Subtype})\frac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v\colon A} \qquad A \leq:_\Phi B}{\Phi \mid \Gamma \vdash v\colon B}) \tag{9.27}$$

Let

$$(\text{Subtype})\frac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash x\colon A} \qquad A' \leq:_\Phi A}{\Phi \mid \Gamma \vdash x\colon A} = \mathit{reduce}(\Delta) \tag{9.28}$$

In

$$(\text{Subtype})\frac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v\colon A'} \qquad A' \leq:_\Phi A \leq:_\Phi B}{\Phi \mid \Gamma \vdash v\colon B} \tag{9.29}$$

Preserves Denotation

$$\begin{aligned} \mathit{before} &= [\![A \leq:_\Phi B]\!] \circ \Delta \\ &= [\![A \leq:_\Phi B]\!] \circ ([\![A' \leq:_\Phi A]\!] \circ \Delta') \quad \text{by Denotation of reduction of } \Delta. \\ &= [\![A' \leq:_\Phi B]\!] \circ \Delta' \quad \text{Subtyping relations are unique} \\ &= \mathit{after} \end{aligned}$$

Case Return:

reduce **definition** To find:

$$\mathit{reduce}((\text{Return})\frac{\dfrac{\Delta}{\Phi \mid \Gamma \vdash v\colon A}}{\Phi \mid \Gamma \vdash \mathtt{return}\ v : \mathtt{M}_1 A}) \tag{9.30}$$

Let

$$\text{(Subtype)}\frac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v\colon A'} \qquad A' \leq:_{\Phi} A}{\Phi \mid \Gamma \vdash v\colon A} = reduce(\Delta) \tag{9.31}$$

In

$$\text{(Subtype)}\frac{\text{(Return)}\dfrac{\dfrac{\Delta'}{\Phi \mid \Gamma \vdash v\colon A}}{\Phi \mid \Gamma \vdash \mathtt{return}\ v : \mathtt{M}_{\mathtt{1}} A'} \qquad \text{(T-Effect)}\dfrac{\mathtt{1} \leq_{\Phi} \mathtt{1} \qquad A' \leq:_{\Phi} A}{\mathtt{M}_{\mathtt{1}} A' \leq:_{\Phi} \mathtt{M}_{\mathtt{1}} A}}{\Phi \mid \Gamma \vdash \mathtt{return}\ v : \mathtt{M}_{\mathtt{1}} A} \tag{9.32}$$

Preserves Denotation Then

$$\begin{aligned}
before &= \eta_A \circ \Delta \quad \text{By definition} \quad \text{By defintion} \\
&= \eta_A \circ [\![A' \leq:_{\Phi} A]\!] \circ \Delta' \quad \text{By reduction of } \Delta \\
&= T_{\mathtt{1}} [\![A' \leq:_{\Phi} A]\!] \circ \eta_{A'} \circ \Delta' \quad \text{By naturality of } \eta \\
&= [\![\mathtt{1} \leq_{\Phi} \mathtt{1}]\!]_{M,A} \circ T_{\mathtt{1}} [\![A' \leq:_{\Phi} A]\!] \circ \eta_{A'} \circ \Delta' \quad \text{Since } [\![\mathtt{1} \leq_{\Phi} \mathtt{1}]\!] \text{ is the identity Nat-Trans} \\
&= after \quad \text{By definition}
\end{aligned}$$

Case Apply:

***reduce* definition** To find:

$$reduce(\text{(Apply)}\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v_1\colon A \to B} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma \vdash v_2\colon A}}{\Phi \mid \Gamma \vdash v_1\ v_2\colon B}) \tag{9.33}$$

Let

$$\text{(Subtype)}\frac{\dfrac{\Delta'_1}{\Phi \mid \Gamma \vdash v_1\colon A' \to B'} \qquad A' \to B' \leq:_{\Phi} A \to B}{\Phi \mid \Gamma \vdash v_1\colon A \to B} = reduce(\Delta_1)$$

$$\text{(Subtype)}\frac{\dfrac{\Delta'_2}{\Phi \mid \Gamma \vdash v\colon A'} \qquad A' \leq:_{\Phi} A}{\Phi \mid \Gamma \vdash v_1\colon A} = reduce(\Delta_2)$$

In

$$\text{(Subtype)}\frac{\text{(Apply)}\dfrac{\dfrac{\Delta'_1}{\Phi \mid \Gamma \vdash v_1\colon A' \to B'} \qquad \text{(Subtype)}\dfrac{\dfrac{\Delta'_2}{\Phi \mid \Gamma \vdash v_2\colon A''} \qquad A'' \leq:_{\Phi} A \leq:_{\Phi} A'}{\Phi \mid \Gamma \vdash v_2\colon A'}}{\Phi \mid \Gamma \vdash v_1\ v_2\colon B'} \qquad B' \leq:_{\Phi} B}{\Phi \mid \Gamma \vdash v_1\ v_2\colon B} \tag{9.34}$$

Preserves Denotation Let

$$f = [\![A \leq:_\Phi A']\!] : A \to A'$$
$$f' = [\![A'' \leq:_\Phi A]\!] : A'' \to A$$
$$g = [\![B' \leq:_\Phi B]\!] : B' \to B$$

Hence

$$\begin{aligned}[\![A' \to B' \leq:_\Phi A \to B]\!] &= (g)^A \circ (B')^f \\ &= \mathtt{cur}(\mathit{app} \circ \mathtt{app}) \circ \mathtt{cur}(\mathtt{app} \circ (\mathtt{Id} \times f)) \\ &= \mathtt{cur}(g \circ \mathtt{app} \circ (\mathtt{Id} \times f))\end{aligned}$$

Then

$$\begin{aligned}\mathit{before} &= \mathtt{app} \circ \langle \Delta_1, \Delta_2 \rangle \quad \text{By definition} \\ &= \mathtt{app} \circ \langle \mathtt{cur}(g \circ \mathtt{app} \circ (\mathtt{Id} \times f)) \circ \Delta_1', f' \circ \Delta_2' \rangle \quad \text{By reductions of } \Delta_1, \Delta_2 \\ &= \mathtt{app} \circ (\mathtt{cur}(g \circ \mathtt{app} \circ (\mathtt{Id} \times f)) \times \mathtt{Id}_A) \circ \langle \Delta_1', f' \circ \Delta_2' \rangle \quad \text{Factoring out} \\ &= g \circ \mathtt{app} \circ (\mathtt{Id} \times f) \circ \langle \Delta_1', f' \circ \Delta_2' \rangle \quad \text{By the exponential property} \\ &= g \circ \mathtt{app} \circ \langle \Delta_1', f \circ f' \circ \Delta_2' \rangle \\ &= \mathit{after} \quad \text{By defintion}\end{aligned}$$

Case If:

reduce **definition**

$$\mathit{reduce}((\text{If})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v\colon \mathtt{Bool}} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma \vdash v_1\colon A} \qquad \dfrac{\Delta_3}{\Phi \mid \Gamma \vdash v_2\colon A}}{\Phi \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : A})$$
$$= (\text{If})\frac{\dfrac{\mathit{reduce}(\Delta_1)}{\Phi \mid \Gamma \vdash v\colon \mathtt{Bool}} \qquad \dfrac{\mathit{reduce}(\Delta_2)}{\Phi \mid \Gamma \vdash v_1\colon A} \qquad \dfrac{\mathit{reduce}(\Delta_3)}{\Phi \mid \Gamma \vdash v_2\colon A}}{\Phi \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : A}$$

Preserves Denotation Since calling *reduce* on the Subderivations preserves their denotations, this definition trivially preserves the denotation of the derivation.

Case Bind:

reduce **definition** To find

$$\mathit{reduce}((\text{Bind})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v_1\colon \mathtt{M}_{\epsilon_1} A} \qquad \dfrac{\Delta_2}{\Phi \mid \Gamma, x\colon A \vdash v_2\colon \mathtt{M}_{\epsilon_2} B}}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B}) \tag{9.35}$$

Let

$$(\text{Subtype})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma \vdash v_1\colon \mathtt{M}_{\epsilon_1'} A'} \qquad (\text{T-Effect})\dfrac{\epsilon_1' \leq_\Phi \epsilon_1 \qquad A' \leq:_\Phi A}{\mathtt{M}_{\epsilon_1'} A' \leq:_\Phi \mathtt{M}_{\epsilon_1} A}}{\Phi \mid \Gamma \vdash v_1\colon \mathtt{M}_{\epsilon_1} A} = \mathit{reduce}(\Delta_1) \tag{9.36}$$

Since $\Phi \vdash (i, \times) \colon (\Gamma, x : A') \triangleright (\Gamma, x \colon A)$ if $A' \leq :_\Phi A$, and by $\Delta_2 = \Phi \mid (\Gamma, x \colon A) \vdash v_2 \colon \mathtt{M}_{\epsilon_2} B$, there also exists a derivation Δ_3 of $\Phi \mid (\Gamma, x : A') \vdash v_2 \colon \mathtt{M}_{\epsilon_2} B$. Δ_3 is derived from Δ_2 simply by inserting a (Subtype) rule below all instances of the (Var) rule.

Let

$$\text{(Subtype)}\dfrac{\dfrac{\Delta_3'}{\Phi \mid \Gamma, x : A' \vdash v_2 \colon \mathtt{M}_{\epsilon_2'} B'} \qquad \text{(T-Effect)}\dfrac{\epsilon_1' \leq_\Phi \epsilon_2 \qquad B' \leq :_\Phi B}{\mathtt{M}_{\epsilon_1'} B' \leq :_\Phi \mathtt{M}_{\epsilon_2} B}}{\Phi \mid \Gamma, x : A' \vdash v_2 \colon \mathtt{M}_{\epsilon_2} B} = reduce(\Delta_3) \tag{9.37}$$

Since the effects monoid operation is monotone, if $\epsilon_1 \leq_\Phi \epsilon_1'$ and $\epsilon_2 \leq_\Phi \epsilon_2'$ then $\epsilon_1 \cdot \epsilon_2 \leq_\Phi \epsilon_1' \cdot \epsilon_2'$

Then the result of reduction of the whole bind expression is:

$$\text{(Subtype)}\dfrac{\text{(Bind)}\dfrac{\dfrac{\Delta_1'}{\Phi \mid \Gamma \vdash v_1 \colon \mathtt{M}_{\epsilon_1'} A'} \qquad \dfrac{\Delta_3'}{\Phi \mid \Gamma, x : A' \vdash v_2 \colon \mathtt{M}_{\epsilon_2'} B'}}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1' \cdot \epsilon_2'} B} \qquad \text{(T-Effect)}\dfrac{\epsilon_1' \cdot \epsilon_2' \leq_\Phi \epsilon_1 \cdot \epsilon_2 \qquad B' \leq :_\Phi B}{\mathtt{M}_{\epsilon_1' \cdot \epsilon_2'} B' \leq :_\Phi \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B}}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B} \tag{9.38}$$

Preserves Denotation Let

$$\begin{aligned}
f &= [\![A' \leq :_\Phi A]\!] : A' \to A \\
g &= [\![B' \leq :_\Phi B]\!] : B' \to B \\
h_1 &= [\![\epsilon_1' \leq_\Phi \epsilon_1]\!] : T_{\epsilon_1'} \to T_{\epsilon_1} \\
h_2 &= [\![\epsilon_2' \leq_\Phi \epsilon_2]\!] : T_{\epsilon_2'} \to T_{\epsilon_2} \\
h &= [\![\epsilon_1' \cdot \epsilon_2' \leq_\Phi \epsilon_1 \cdot \epsilon_2]\!] : T_{\epsilon_1' \cdot \epsilon_2'} \to T_{\epsilon_1 \cdot \epsilon_2}
\end{aligned}$$

Due to the denotation of the weakening used to derive Δ_3 from Δ_2, we have

$$\Delta_3 = \Delta_2 \circ (\mathtt{Id}_\Gamma \times f) \tag{9.39}$$

And due to the reduction of Δ_3, we have

$$\Delta_3 = h_{2,B} \circ T_{\epsilon_2'} g \circ \Delta_3' \tag{9.40}$$

So:

$$\begin{aligned}
before &= \mu_{\epsilon_1,\epsilon_2,B} \circ T_{\epsilon_1} \Delta_2 \circ \mathsf{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, \Delta_1 \rangle \quad \text{By definition.} \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ T_{\epsilon_1} \Delta_2 \circ \mathsf{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, h_{1,A} \circ T_{\epsilon_1'} f \circ \Delta_1' \rangle \quad \text{By reduction of } \Delta_1. \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ T_{\epsilon_1} \Delta_2 \circ \mathsf{t}_{\epsilon_1,\Gamma,A} \circ (\mathtt{Id}_\Gamma \times h_{1,A}) \circ \langle \mathtt{Id}_\Gamma, T_{\epsilon_1'} f \circ \Delta_1' \rangle \quad \text{Factor out } h_1 \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ T_{\epsilon_1} \Delta_2 \circ h_{1,(\Gamma \times A)} \circ \mathsf{t}_{\epsilon_1',\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, T_{\epsilon_1'} f \circ \Delta_1' \rangle \quad \text{Tensor strength and subeffecting } h_1 \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ h_{1,B} \circ T_{\epsilon_1'} \Delta_2 \circ \mathsf{t}_{\epsilon_1',\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, T_{\epsilon_1'} f \circ \Delta_1' \rangle \quad \text{Naturality of } h_1 \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ h_{1,B} \circ T_{\epsilon_1'} \Delta_2 \circ \mathsf{t}_{\epsilon_1',\Gamma,A} \circ (\mathtt{Id}_\Gamma \times T_{\epsilon_1'} f) \circ \langle \mathtt{Id}_\Gamma, \Delta_1' \rangle \quad \text{Factor out pairing again} \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ h_{1,B} \circ T_{\epsilon_1'} (\Delta_2 \circ (\mathtt{Id}_\Gamma \times f)) \circ \mathsf{t}_{\epsilon_1',\Gamma,A'} \circ \langle \mathtt{Id}_\Gamma, \Delta_1' \rangle \quad \text{Tensorstrength} \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ h_{1,B} \circ T_{\epsilon_1'} (\Delta_3) \circ \mathsf{t}_{\epsilon_1',\Gamma,A'} \circ \langle \mathtt{Id}_\Gamma, \Delta_1' \rangle \quad \text{By the definition of } \Delta_3 \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ h_{1,B} \circ T_{\epsilon_1'} (h_{2,B} \circ T_{\epsilon_2'} g \circ \Delta_3') \circ \mathsf{t}_{\epsilon_1',\Gamma,A'} \circ \langle \mathtt{Id}_\Gamma, \Delta_1' \rangle \quad \text{By the reduction of } \Delta_3 \\
&= \mu_{\epsilon_1,\epsilon_2,B} \circ h_{1,B} \circ T_{\epsilon_1'} h_{2,B} \circ T_{\epsilon_1'} T_{\epsilon_2'} g \circ T_{\epsilon_1'} \Delta_3' \circ \mathsf{t}_{\epsilon_1',\Gamma,A'} \circ \langle \mathtt{Id}_\Gamma, \Delta_1' \rangle \quad \text{Factor out the functor} \\
&= h_B \circ \mu_{\epsilon_1',\epsilon_2',B} \circ T_{\epsilon_1'} T_{\epsilon_2'} g \circ T_{\epsilon_1'} \Delta_3' \circ \mathsf{t}_{\epsilon_1',\Gamma,A'} \circ \langle \mathtt{Id}_\Gamma, \Delta_1' \rangle \quad \text{By the } \mu \text{ and Subtype rule} \\
&= h_B \circ T_{\epsilon_1' \cdot \epsilon_2'} g \circ \mu_{\epsilon_1',\epsilon_2',B'} \circ T_{\epsilon_1'} \Delta_3' \circ \mathsf{t}_{\epsilon_1',\Gamma,A'} \circ \langle \mathtt{Id}_\Gamma, \Delta_1' \rangle \quad \text{By naturality of } \mu_{,,} \\
&= after \quad \text{By definition}
\end{aligned}$$

Case Effect-Gen:

reduce **definition** To find

$$reduce((\text{Effect-Gen})\frac{\dfrac{\Delta_1}{\Phi, \alpha \mid \Gamma \vdash v : A}}{\Phi \mid \Gamma \vdash \Lambda\alpha.v : \forall\alpha.A}) \tag{9.41}$$

Let

$$(\text{Subtype})\frac{\dfrac{\Delta_1'}{\Phi, \alpha \mid \Gamma \vdash v : A'} \qquad A' \leq:_\Phi A}{\Phi, \alpha \mid \Gamma \vdash v : A} = reduce(\Delta_1) \tag{9.42}$$

in

$$(\text{Subtype})\frac{(\text{Effect-Gen})\dfrac{\dfrac{\Delta_1'}{\Phi, \alpha \mid \Gamma \vdash v : A'}}{\Phi \mid \Gamma \vdash \Lambda\alpha.v : \forall\alpha.A'} \qquad (\text{S-Quantification})\dfrac{A' \leq:_{\Phi,\alpha} A}{\forall\alpha.A' \leq:_\Phi \forall\alpha.A}}{\Phi \mid \Gamma \vdash \Lambda\alpha.v : \forall\alpha.A} \tag{9.43}$$

Preserves Denotation

$$\begin{aligned} before &= \overline{\Delta_1} \\ &= \overline{[\![A' \leq:_{\Phi,\alpha} A]\!] \circ \Delta_1'} \quad \text{By induction} \\ &= \forall_I([\![A' \leq:_{\Phi,\alpha} A]\!]) \circ \overline{\Delta_1'} \\ &= [\![\forall\alpha.A' \leq:_\Phi \forall\alpha.A]\!] \circ \overline{\Delta_1'} \quad \text{By definition} \\ &= after \quad \text{By definition} \end{aligned}$$

Case Effect-Spec:

reduce **definition** To find

$$reduce((\text{Effect-Spec})\frac{\dfrac{\Delta_1}{\Phi \mid \Gamma \vdash v : \forall\alpha.A} \qquad \Phi\epsilon}{\Phi \mid \Gamma \vdash v\ \epsilon : A[\epsilon/\alpha]}) \tag{9.44}$$

Let

$$(\text{Subtype})\frac{\dfrac{\Delta_1'}{\Phi \mid \Gamma \vdash v : \forall\alpha.A'} \qquad (\text{S-Quantification})\dfrac{A' \leq:_{\Phi,\alpha} A}{\forall\alpha.A' \leq:_\Phi \forall\alpha.A}}{\Phi \mid \Gamma \vdash v : \forall\alpha.A} = reduce(\Delta_1) \tag{9.45}$$

In

$$\text{(Subtype)}\frac{\text{(Effect-Spec)}\dfrac{\dfrac{\Delta_1'}{\Phi \mid \Gamma \vdash v\colon \forall\alpha.A} \qquad \Phi\epsilon}{\Phi \mid \Gamma \vdash v\ \epsilon\colon A[\epsilon/\alpha]} \qquad A'[\epsilon/\alpha] \leq:_{\Phi} A[\epsilon/\alpha]}{\Phi \mid \Gamma \vdash v\ \epsilon\colon A[\epsilon/\alpha]} \tag{9.46}$$

Preserves Denotation Let

$$\begin{aligned} h &= [\![\Phi \vdash \epsilon\colon \texttt{Effect}]\!] \\ A &= [\![\Phi, \beta \vdash A[\beta/\alpha]\colon \texttt{Effect}]\!] \\ A' &= [\![\Phi, \beta \vdash A'[\beta/\alpha]\colon \texttt{Effect}]\!] \end{aligned}$$

Note that

$$\langle \texttt{Id}_I, h\rangle^*(\pi_1^*(f)) = (\pi_1 \circ \langle \texttt{Id}_I, h\rangle)^*(f) = \texttt{Id}_I^*(f) = f \tag{9.47}$$

And that

$$\langle \texttt{Id}_I, h\rangle = [\![\Phi \vdash [\epsilon/\alpha]\colon \Phi, \alpha]\!] \tag{9.48}$$

With lemma:

$$\begin{aligned} [\![\forall\alpha.A' \leq:_{\Phi} \forall\alpha.A]\!] &= \forall_I([\![A' \leq:_{\Phi,\alpha} A]\!]) \\ &= \langle \texttt{Id}_I, h\rangle^*(\pi_1^*(\forall_I([\![A' \leq:_{\Phi,\alpha} A]\!]))) \end{aligned}$$

In

$$\begin{aligned} before &= \langle \texttt{Id}_I, h\rangle^*(\epsilon_A) \circ \Delta_1 \\ &= \langle \texttt{Id}_I, h\rangle^*(\epsilon_A) \circ [\![\forall\alpha.A' \leq:_{\Phi} \forall\alpha.A]\!] \circ \Delta_1' \quad \text{By induction} \\ &= \langle \texttt{Id}_I, h\rangle^*(\epsilon_A) \circ \langle \texttt{Id}_I, h\rangle^*(\pi_1^*(\forall_I([\![A' \leq:_{\Phi,\alpha} A]\!]))) \circ \Delta_1' \quad \text{By lemma} \\ &= \langle \texttt{Id}_I, h\rangle^*(\epsilon_A \circ \pi_1^*(\forall_I([\![A' \leq:_{\Phi,\alpha} A]\!]))) \circ \Delta_1' \quad \text{By functorality} \\ &= \langle \texttt{Id}_I, h\rangle^*([\![A' \leq:_{\Phi,\alpha} A]\!] \circ \epsilon_{A'}) \circ \Delta_1' \quad \text{By Naturality} \\ &= \langle \texttt{Id}_I, h\rangle^*([\![A' \leq:_{\Phi,\alpha} A]\!]) \circ \langle \texttt{Id}_I, h\rangle^*(\epsilon_{A'}) \circ \Delta_1' \\ &= [\![A'[\epsilon/\alpha] \leq:_{\Phi,\alpha} A[\epsilon/\alpha]]\!] \circ \langle \texttt{Id}_I, h\rangle^*(\epsilon_{A'}) \circ \Delta_1' \quad \text{By substitution of subtyping} \\ &= after \end{aligned}$$

□

Theorem 9.3.2 (Denotations are Equivalent). *Any two derivations of the type relation instance $\Phi \mid \Gamma \vdash v\colon A$ have the same denotation.*

Proof: For each type relation instance $\Phi \mid \Gamma \vdash v\colon A$ there exists a unique reduced derivation of the relation instance. For all derivations Δ, Δ' of the type relation instance, $[\![\Delta]\!] = [\![reduce \Delta]\!] = [\![reduce \Delta']\!] = [\![\Delta']\!]$, hence the denotation $[\![\Phi \mid \Gamma \vdash v\colon A]\!]$ is unique.

Chapter 10

Equational-Equivalence Theorem (Soundness)

10.1 Equational Equivalence Relation

The equational equivalence relation is a rule based relation with three main flavours of rules. These are a set of rules that model a monadic reduction system of the language, a set of congruence relation rules, and rules that extend the system into an equivalence relation.

Reduction-based rules

$$\text{(Eq-Lambda-Beta)}\frac{\Phi \mid \Gamma, x\colon A \vdash v_2\colon B \qquad \Phi \mid \Gamma \vdash v_1\colon A}{\Phi \mid \Gamma \vdash (\lambda x\colon A.v_1\ )\ v_2 \approx v_1[v_2/x]\colon B} \quad \text{(Eq-Lambda-Eta)}\frac{\Phi \mid \Gamma \vdash v\colon A \to B}{\Phi \mid \Gamma \vdash \lambda x\colon A.(v\ x\ ) \approx v\colon A \to B}$$

$$\text{(Eq-Left-Unit)}\frac{\Phi \mid \Gamma \vdash v_1\colon A \qquad \Phi \mid \Gamma, x\colon A \vdash v_2\colon \mathtt{M}_\epsilon B}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow \mathtt{return}\ v_1\ \ \mathtt{in}\ v_2\ \approx v_2[v_1/x]\colon \mathtt{M}_\epsilon B} \quad \text{(Eq-Right-Unit)}\frac{\Phi \mid \Gamma \vdash v\colon \mathtt{M}_\epsilon A}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v\ \mathtt{in}\ \mathtt{return}\ x\ \ \approx v\colon \mathtt{M}_\epsilon A}$$

$$\text{(Eq-Associativity)}\frac{\Phi \mid \Gamma \vdash v_1\colon \mathtt{M}_{\epsilon_1} A \qquad \Phi \mid \Gamma, x\colon A \vdash v_2\colon \mathtt{M}_{\epsilon_2} B \qquad \Phi \mid \Gamma, y\colon B \vdash v_3\colon \mathtt{M}_{\epsilon_3} C}{\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ (\mathtt{do}\ y \leftarrow v_2\ \mathtt{in}\ v_3\ ) \approx \mathtt{do}\ y \leftarrow (\mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2\ )\ \mathtt{in}\ v_3\ \colon \mathtt{M}_{\epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3} C}$$

$$\text{(Eq-Unit)}\frac{\Phi \mid \Gamma \vdash v\colon \mathtt{Unit}}{\Phi \mid \Gamma \vdash v \approx \mathtt{()}\colon \mathtt{Unit}}$$

$$\text{(Eq-If-True)}\frac{\Phi \mid \Gamma \vdash v_1\colon A \qquad \Phi \mid \Gamma \vdash v_2\colon A}{\Phi \mid \Gamma \vdash \mathtt{if}_A\ \mathtt{true}\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2\ \ \approx v_1\colon A} \quad \text{(Eq-If-False)}\frac{\Phi \mid \Gamma \vdash v_2\colon A \qquad \Phi \mid \Gamma \vdash v_1\colon A}{\Phi \mid \Gamma \vdash \mathtt{if}_A\ \mathtt{false}\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2\ \ \approx v_2\colon A}$$

$$\text{(Eq-If-Eta)}\frac{\Phi \mid \Gamma, x : \mathtt{Bool} \vdash v_2\colon A \qquad \Phi \mid \Gamma \vdash v_1\colon \mathtt{Bool}}{\Phi \mid \Gamma \vdash \mathtt{if}_A\ v_1\ \mathtt{then}\ v_2[\mathtt{true}/x]\ \mathtt{else}\ v_2[\mathtt{false}/x]\ \ \approx v_2[v_1/x]\colon A}$$

$$\text{(Eq-Effect-Beta)}\frac{\Phi\epsilon \qquad \Phi, \alpha \mid \Gamma \vdash v\colon A}{\Phi \mid \Gamma \vdash (\Lambda\alpha.v\ \epsilon) \approx v[\epsilon/\alpha]\colon A[\epsilon/\alpha]} ntreeruleIEq - Effect - Eta\Phi \mid \Gamma \vdash v\colon \forall\alpha.A\Phi \mid \Gamma \vdash \Lambda\alpha.(v\ \alpha) \approx v\colon \forall\alpha.A$$

Congruence rules

$$\text{(Eq-Effect-Gen)}\frac{\Phi, \alpha \mid \Gamma \vdash v_1 \approx v_2 \colon A}{\Phi \mid \Gamma \vdash \Lambda\alpha.v_1 \approx \Lambda\alpha.v_2 \colon \forall\alpha.A} \quad \text{(Eq-Effect-Spec)}\frac{\Phi \mid \Gamma \vdash v_1 \approx v_2 \colon \forall\alpha.A \qquad \Phi\epsilon}{\Phi \mid \Gamma \vdash v_1\ \epsilon \approx v_2\ \epsilon \colon A[\epsilon/\alpha]}$$

$$\text{(Eq-Fn)}\frac{\Phi \mid \Gamma, x \colon A \vdash v_1 \approx v_2 \colon B}{\Phi \mid \Gamma \vdash \lambda x \colon A.v_1 \ \approx \lambda x \colon A.v_2 : A \to B} \quad \text{(Eq-Return)}\frac{\Phi \mid \Gamma \vdash v_1 \approx v_2 \colon A}{\Phi \mid \Gamma \vdash \texttt{return}\ v_1 \ \approx \texttt{return}\ v_2 : \texttt{M}_1 A}$$

$$\text{(Eq-Apply)}\frac{\Phi \mid \Gamma \vdash v_1 \approx v_1' \colon A \to B \qquad \Phi \mid \Gamma \vdash v_2 \approx v_2' \colon A}{\Phi \mid \Gamma \vdash v_1\ v_2 \approx v_1'\ v_2' \colon B} \quad \text{(Eq-Bind)}\frac{\Phi \mid \Gamma \vdash v_1 \approx v_1' \colon \texttt{M}_{\epsilon_1} A \qquad \Phi \mid \Gamma, x \colon A \vdash v_2 \approx v_2' \colon \texttt{M}_{\epsilon_2} B}{\Phi \mid \Gamma \vdash \texttt{do}\ x \leftarrow v_1\ \texttt{in}\ v_2 \ \approx \texttt{do}\ x \leftarrow v_1'\ \texttt{in}\ v_2' : \texttt{M}_{\epsilon_1 \cdot \epsilon_2} B}$$

$$\text{(Eq-If)}\frac{\Phi \mid \Gamma \vdash v \approx v' \colon \texttt{Bool} \qquad \Phi \mid \Gamma \vdash v_1 \approx v_1' \colon A \qquad \Phi \mid \Gamma \vdash v_2 \approx v_2' \colon A}{\Phi \mid \Gamma \vdash \texttt{if}_A\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2 \ \approx \texttt{if}_A\ v'\ \texttt{then}\ v_1'\ \texttt{else}\ v_2' : A} \quad \text{(Eq-Subtype)}\frac{\Phi \mid \Gamma \vdash v \approx v' \colon A \qquad A {\leq :_\Phi} B}{\Phi \mid \Gamma \vdash v \approx v' \colon B}$$

We extend the relation to an equivalence relation as so:

$$\text{(Eq-Reflexive)}\frac{\Phi \mid \Gamma \vdash v \colon A}{\Phi \mid \Gamma \vdash v \approx v \colon A} \quad \text{(Eq-Symmetric)}\frac{\Phi \mid \Gamma \vdash v_1 \approx v_2 \colon A}{\Phi \mid \Gamma \vdash v_2 \approx v_1 \colon A}$$

$$\text{(Eq-Transitive)}\frac{\Phi \mid \Gamma \vdash v_1 \approx v_2 \colon A \qquad \Phi \mid \Gamma \vdash v_2 \approx v_3 \colon A}{\Phi \mid \Gamma \vdash v_1 \approx v_3 \colon A}$$

10.2 Soundness

Theorem 10.2.1 (Soundness)**.** *If* $\Phi \mid \Gamma \vdash v \approx v' \colon A$ *then* $[\![\Gamma \vdash v \colon A]\!] = [\![\Gamma \vdash v' \colon A]\!]$

Proof: By induction over equational equivalence relation.

10.2.1 Equivalence Relation

The cases over the equivalence relation laws hold by the uniqueness of denotations and the fact that equality over morphisms is an equivalence relation.

Case Eq-Reflexive: Equality is reflexive, so if $\Phi \mid \Gamma \vdash v \colon A$ then $[\![\Phi \mid \Gamma \vdash v \colon A]\!]$ is equal to itself.

Case Eq-Symmetric: By inversion, if $\Phi \mid \Gamma \vdash v \approx v' \colon A$ then $\Phi \mid \Gamma \vdash v' \approx v \colon A$, so by induction $[\![\Gamma \vdash v' \colon A]\!] = [\![\Gamma \vdash v \colon A]\!]$ and hence $[\![\Gamma \vdash v \colon A]\!] = [\![\Gamma \vdash v' \colon A]\!]$

Case Eq-Transitive: There must exist v_2 such that $\Phi \mid \Gamma \vdash v_1 \approx v_2 \colon A$ and $\Phi \mid \Gamma \vdash v_2 \approx v_3 \colon A$, so by induction, $[\![\Gamma \vdash v_1 \colon A]\!] = [\![\Gamma \vdash v_2 \colon A]\!]$ and $[\![\Gamma \vdash v_2 \colon A]\!] = [\![\Gamma \vdash v_3 \colon A]\!]$. Hence by transitivity of equality, $[\![\Gamma \vdash v_1 \colon A]\!] = [\![\Gamma \vdash v_3 \colon A]\!]$

10.2.2 Reduction Conversions

These cases are typically proved using the properties of a cartesian closed category with a strong graded monad.

Case Eq-Lambda-Beta: Let $f = [\![\Phi \mid \Gamma, x \colon A \vdash v_1 \colon B]\!] : (\Gamma \times A) \to B$

Let $g = [\![\Phi \mid \Gamma \vdash v_2 \colon A]\!] : \Gamma \to A$

By the substitution denotation,

$$[\![\Phi \mid \Gamma \vdash [v_2/x] \colon \Gamma, x \colon A]\!] : \Gamma \to (\Gamma \times A) = \langle \mathtt{Id}_\Gamma, g\rangle$$

We have

$$[\![\Phi \mid \Gamma \vdash v_1[{}_2v/x] \colon B]\!] = f \circ \langle \mathtt{Id}_\Gamma, g\rangle$$

and hence

$$\begin{aligned}
[\![\Phi \mid \Gamma \vdash (\lambda x \colon A.v\ )\ v \colon B]\!] &= \mathtt{app} \circ \langle \mathtt{cur}(f), g\rangle \\
&= \mathtt{app} \circ (\mathtt{cur}(f) \times \mathtt{Id}_A) \circ \langle \mathtt{Id}_\Gamma, g\rangle \\
&= f \circ \langle \mathtt{Id}_\Gamma, g\rangle \\
&= [\![\Phi \mid \Gamma \vdash v_1[v_2/x] \colon B]\!]
\end{aligned}$$

Case Eq-Left-Unit: Let $f = [\![\Phi \mid \Gamma, x \colon A \vdash v_1 \colon \mathtt{M}_\epsilon B]\!]$

Let $g = [\![\Phi \mid \Gamma \vdash v_2 \colon A]\!] : \Gamma \to A$

By the substitution denotation,

$$[\![\Phi \mid \Gamma \vdash [v_2/x] \colon \Gamma, x \colon A]\!] : \Gamma \to (\Gamma \times A) = \langle \mathtt{Id}_\Gamma, g\rangle$$

We have

$$[\![\Phi \mid \Gamma \vdash v_1[v_2/x] \colon \mathtt{M}_\epsilon B]\!] = f \circ \langle \mathtt{Id}_\Gamma, g\rangle$$

And hence

$$\begin{aligned}
&[\![\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow \mathtt{return}\ v_2\ \ \mathtt{in}\ v_1 : \mathtt{M}_\epsilon B]\!] \\
=&\mu_{1,\epsilon,B} \circ T_1 f \circ \mathtt{t}_{1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, \eta_A \circ g\rangle \\
=&\mu_{1,\epsilon,B} \circ T_1 f \circ \mathtt{t}_{1,\Gamma,A} \circ (\mathtt{Id}_\Gamma \times \eta_A) \circ \langle \mathtt{Id}_\Gamma, g\rangle \\
=&\mu_{1,\epsilon,B} \circ T_1 f \circ \eta_{(\Gamma\times A)} \circ \langle \mathtt{Id}_\Gamma, g\rangle \quad \text{By Tensor strength + unit} \\
=&\mu_{1,\epsilon,B} \circ \eta_{T_\epsilon B} \circ f \circ \langle \mathtt{Id}_\Gamma, g\rangle \quad \text{By Naturality of } \eta \\
=&f \circ \langle \mathtt{Id}_\Gamma, g\rangle \quad \text{By left unit law} \\
=&[\![\Phi \mid \Gamma \vdash v_1[v_2/x] \colon \mathtt{M}_\epsilon B]\!]
\end{aligned}$$

Case Eq-Associativity: Let $f = [\![\Phi \mid \Gamma \vdash v \colon \mathtt{M}_{\epsilon} A]\!]$

$$\begin{aligned}
[\![\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v\ \mathtt{in}\ \mathtt{return}\ x\ \ \colon \mathtt{M}_{\epsilon} A]\!] &= \mu_{\epsilon,\mathtt{1},A} \circ T_{\epsilon}(\eta_A \circ \pi_2) \circ \mathtt{t}_{\epsilon,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \\
&= T_{\epsilon}\pi_2 \circ \mathtt{t}_{\epsilon,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \\
&= \pi_2 \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \\
&= f
\end{aligned}$$

Case Eq-Associativity: Let

$$\begin{aligned}
f &= [\![\Phi \mid \Gamma \vdash v_1 \colon \mathtt{M}_{\epsilon_1} A]\!] \\
g &= [\![\Phi \mid \Gamma, x \colon A \vdash v_2 \colon \mathtt{M}_{\epsilon_2} B]\!] \\
h &= [\![\Phi \mid \Gamma, y \colon B \vdash v_3 \colon \mathtt{M}_{\epsilon_3} C]\!]
\end{aligned}$$

We also have the weakening:

$$\Phi \vdash \iota\pi\times \colon \Gamma, x \colon A, y : B \triangleright \Gamma, y \colon B \tag{10.1}$$

With denotation:

$$[\![\Phi \vdash \iota\pi\times \colon \Gamma, x \colon A, y : B \triangleright \Gamma, y \colon B]\!] = (\pi_1 \times \mathtt{Id}_B) \tag{10.2}$$

We need to prove that the following are equal

$$\begin{aligned}
&lhs = [\![\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ (\mathtt{do}\ y \leftarrow v_2\ \mathtt{in}\ v_3\ ) \colon \mathtt{M}_{\epsilon_1 \cdot \epsilon_2 \cdot \epsilon_2} C]\!] \\
&= \mu_{\epsilon_1, \epsilon_2 \cdot \epsilon_3, C} \circ T_{\epsilon_1}(\mu_{\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_2} h \circ (\pi_1 \times \mathtt{Id}_B) \circ \mathtt{t}_{\epsilon_2,(\Gamma\times A),B} \circ \langle \mathtt{Id}_{(\Gamma\times A)}, g \rangle) \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \\
&rhs = [\![\Phi \mid \Gamma \vdash \mathtt{do}\ y \leftarrow (\mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2\ )\ \mathtt{in}\ v_3 \colon \mathtt{M}_{\epsilon_1 \cdot \epsilon_2 \cdot \epsilon_2} C]\!] \\
&= \mu_{\epsilon_1\cdot\epsilon_2, \epsilon_3, C} \circ T_{\epsilon_1\cdot\epsilon_2}(h) \circ \mathtt{t}_{\epsilon_1\cdot\epsilon_2,\Gamma,B} \circ \langle \mathtt{Id}_{\Gamma}, (\mu_{\epsilon_1,\epsilon_2,B} \circ T_{\epsilon_1} g \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle) \rangle
\end{aligned}$$

Let's look at fragment F of rhs.

$$F = \mathtt{t}_{\epsilon_1\cdot\epsilon_2,\Gamma,B} \circ \langle \mathtt{Id}_{\Gamma}, (\mu_{\epsilon_1,\epsilon_2,B} \circ T_{\epsilon_1} g \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle) \rangle \tag{10.3}$$

So

$$rhs = \mu_{\epsilon_1\cdot\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_1\cdot\epsilon_2}(h) \circ F \tag{10.4}$$

$$\begin{aligned}
F &= \mathtt{t}_{\epsilon_1\cdot\epsilon_2,\Gamma,B} \circ (\mathtt{Id}_{\Gamma} \times \mu_{\epsilon_1,\epsilon_2,B}) \circ (\mathtt{Id}_{\Gamma} \times T_{\epsilon_1} g) \circ \langle \mathtt{Id}_{\Gamma}, \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \rangle \\
&= \mu_{\epsilon_1,\epsilon_2,(\Gamma\times B)} \circ T_{\epsilon_1} \mathtt{t}_{\epsilon_2,\Gamma,B} \circ \mathtt{t}_{\epsilon_1,\Gamma,(T_{\epsilon_2} B)} \circ (\mathtt{Id}_{\Gamma} \circ T_{\epsilon_1} g) \circ \langle \mathtt{Id}_{\Gamma}, \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \rangle \quad \text{By tensor strength commuting with the bind N-T} \\
&= \mu_{\epsilon_1,\epsilon_2,(\Gamma\times B))} \circ T_{\epsilon_1}(\mathtt{t}_{\epsilon_2,\Gamma,B} \circ (\mathtt{Id}_{\Gamma} \times g)) \circ \mathtt{t}_{\epsilon_1,\Gamma,(\Gamma\times A)} \circ \langle \mathtt{Id}_{\Gamma}, \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \rangle \quad \text{By naturality of t-strength}
\end{aligned}$$

Since $rhs = \mu_{\epsilon_1\cdot\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_1\cdot\epsilon_2}(h) \circ F$,

$$\begin{aligned}
rhs =& \mu_{\epsilon_1\cdot\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_1\cdot\epsilon_2}(h) \circ \mu_{\epsilon_1,\epsilon_2,(\Gamma\times B))} \circ T_{\epsilon_1}(\mathtt{t}_{\epsilon_2,\Gamma,B} \circ (\mathtt{Id}_{\Gamma} \times g)) \circ \mathtt{t}_{\epsilon_1,\Gamma,(\Gamma\times A)} \circ \langle \mathtt{Id}_{\Gamma}, \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \rangle \\
=& \mu_{\epsilon_1\cdot\epsilon_2,\epsilon_3,C} \circ \mu_{\epsilon_1,\epsilon_2,(T_{\epsilon_3} C)} \circ T_{\epsilon_1}(T_{\epsilon_2}(h) \circ \mathtt{t}_{\epsilon_2,\Gamma,B} \circ (\mathtt{Id}_{\Gamma} \times g)) \circ \mathtt{t}_{\epsilon_1,\Gamma,(\Gamma\times A)} \circ \langle \mathtt{Id}_{\Gamma}, \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \rangle \quad \text{Naturality of } \mu \\
=& \mu_{\epsilon_1,\epsilon_2\cdot\epsilon_3,C} \circ T_{\epsilon_1}(\mu_{\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_2}(h) \circ \mathtt{t}_{\epsilon_2,\Gamma,B} \circ (\mathtt{Id}_{\Gamma} \times g)) \circ \mathtt{t}_{\epsilon_1,\Gamma,(\Gamma\times A)} \circ \langle \mathtt{Id}_{\Gamma}, \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \rangle
\end{aligned}$$

Let's now look at the fragment G of rhs

$$G = T_{\epsilon_1}(\mathtt{Id}_{\Gamma} \times g) \circ \mathtt{t}_{\epsilon_1,\Gamma,(\Gamma\times A)} \circ \langle \mathtt{Id}_{\Gamma}, \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_{\Gamma}, f \rangle \rangle \tag{10.5}$$

So

$$rhs = \mu_{\epsilon_1,\epsilon_2\cdot\epsilon_3,C} \circ T_{\epsilon_1}(\mu_{\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_2}(h) \circ \mathtt{t}_{\epsilon_2,\Gamma,B}) \circ G \tag{10.6}$$

By folding out the $\langle ..., ... \rangle$, we have

$$G = T_{\epsilon_1}(\mathtt{Id}_\Gamma \times g) \circ \mathtt{t}_{\epsilon_1,\Gamma,\Gamma\times A} \circ (\mathtt{Id}_\Gamma \times \mathtt{t}_{\epsilon_1,\Gamma,A}) \circ \langle \mathtt{Id}_\Gamma, \langle \mathtt{Id}_\Gamma, f \rangle \rangle \tag{10.7}$$

Since tensor strength commutes with, α, the associativity natural transformation on binary products, the following commutes:

$$\begin{tikzcd}
\Gamma \arrow[r, "\langle \mathtt{Id}_\Gamma, \langle \mathtt{Id}_\Gamma, f \rangle \rangle"] & \Gamma \times (\Gamma \times T_{\epsilon_1} A) \arrow[d, "\mathtt{Id}_\Gamma \times \mathtt{t}_{\epsilon_1,\Gamma,A}"] & (\Gamma \times \Gamma) \times T_{\epsilon_1} A \arrow[l, "\alpha_{\Gamma,\Gamma,(T_{\epsilon_1} A)}"'] \arrow[d, "\mathtt{t}_{\epsilon_1,(\Gamma\times\Gamma),A}"] \\
& \Gamma \times T_{\epsilon_1}(\Gamma \times A) \arrow[d, "\mathtt{t}_{\epsilon_1,\Gamma,\Gamma\times A}"] & T_{\epsilon_1}((\Gamma \times \Gamma) \times A) \arrow[dl, "T_{\epsilon_1}\alpha_{\Gamma,\Gamma,A}"] \\
& T_{\epsilon_1}(\Gamma \times (\Gamma \times A)) &
\end{tikzcd}$$

Where $\alpha : ((\_ \times \_) \times \_) \to (\_ \times (\_ \times \_))$ is a natural isomorphism.

$$\begin{aligned}
\alpha &= \langle \pi_1 \circ \pi_1, \langle \pi_2 \circ \pi_1, \pi_2 \rangle \rangle \\
\alpha^{-1} &= \langle \langle \pi_1, \pi_1 \circ \pi_2 \rangle, \pi_2 \circ \pi_2 \rangle
\end{aligned}$$

So:

$$\begin{aligned}
G =& T_{\epsilon_1}((\mathtt{Id}_\Gamma \times g) \circ \alpha_{\Gamma,\Gamma,A}) \circ \mathtt{t}_{\epsilon_1,(\Gamma\times\Gamma),A} \circ \alpha^{-1}_{\Gamma,\Gamma,(T_{\epsilon_1} A)} \circ \langle \mathtt{Id}_\Gamma, \langle \mathtt{Id}_\Gamma, f \rangle \rangle \\
=& T_{\epsilon_1}((\mathtt{Id}_\Gamma \times g) \circ \alpha_{\Gamma,\Gamma,A}) \circ \mathtt{t}_{\epsilon_1,(\Gamma\times\Gamma),A} \circ (\langle \mathtt{Id}_\Gamma, \mathtt{Id}_\Gamma \rangle \times \mathtt{Id}_{T_{\epsilon_1} A}) \circ \langle \mathtt{Id}_\Gamma, f \rangle \quad \text{By definition of } \alpha \text{ and products} \\
=& T_{\epsilon_1}((\mathtt{Id}_\Gamma \times g) \circ \alpha_{\Gamma,\Gamma,A} \circ (\langle \mathtt{Id}_\Gamma, \mathtt{Id}_\Gamma \rangle \times \mathtt{Id}_A)) \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, f \rangle \quad \text{By tensor strength's left-naturality} \\
=& T_{\epsilon_1}((\pi_1 \times \mathtt{Id}_{T_{\epsilon_2} B}) \circ \langle \mathtt{Id}_{(\Gamma\times A)}, g \rangle) \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, f \rangle
\end{aligned}$$

Since

$$rhs = \mu_{\epsilon_1,\epsilon_2\cdot\epsilon_3,C} \circ T_{\epsilon_1}(\mu_{\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_2}(h) \circ \mathtt{t}_{\epsilon_2,\Gamma,B}) \circ G \tag{10.8}$$

We have

$$\begin{aligned}
rhs &= \mu_{\epsilon_1,\epsilon_2\cdot\epsilon_3,C} \circ T_{\epsilon_1}(\mu_{\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_2}(h) \circ \mathtt{t}_{\epsilon_2,\Gamma,B} \circ (\pi_1 \times \mathtt{Id}_{T_{\epsilon_2} B}) \circ \langle \mathtt{Id}_{(\Gamma\times A)}, g \rangle) \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, f \rangle \\
&= \mu_{\epsilon_1,\epsilon_2\cdot\epsilon_3,C} \circ T_{\epsilon_1}(\mu_{\epsilon_2,\epsilon_3,C} \circ T_{\epsilon_2}(h \circ (\pi_1 \times \mathtt{Id}_B)) \circ \mathtt{t}_{\epsilon_2,(\Gamma\times A),B} \circ \langle \mathtt{Id}_{(\Gamma\times A)}, g \rangle) \circ \mathtt{t}_{\epsilon_1,\Gamma,A} \circ \langle \mathtt{Id}_\Gamma, f \rangle \quad \text{By Left-Tensor Strength} \\
&= lhs \quad \text{Woohoo!}
\end{aligned}$$

Case Eq-Lambda-Eta: Let

$$f = [\![\Phi \mid \Gamma \vdash v \colon A \to B]\!] : \Gamma \to (B)^A \tag{10.9}$$

By weakening, we have

$$\begin{aligned}
[\![\Phi \mid \Gamma, x \colon A \vdash v \colon A \to B]\!] &= f \circ \pi_1 : \Gamma \times A \to (B)^A \\
[\![\Phi \mid \Gamma, x \colon A \vdash v\ x \colon B]\!] &= \mathtt{app} \circ \langle f \circ \pi_1, \pi_2 \rangle
\end{aligned}$$

Hence, we have

$$
\begin{aligned}
[\![\Phi \mid \Gamma \vdash \lambda x\colon A.(v\ x) : A \to B]\!] &= \mathtt{cur}(\mathtt{app} \circ \langle f \circ \pi_1, \pi_2\rangle) \\
\mathtt{app} \circ ([\![\Phi \mid \Gamma \vdash \lambda x\colon A.(v\ x) : A \to B]\!] \times \mathtt{Id}_A) &= \mathtt{app} \circ (\mathtt{cur}(\mathtt{app} \circ \langle f \circ \pi_1, \pi_2\rangle) \times \mathtt{Id}_A) \\
&= \mathtt{app} \circ \langle f \circ \pi_1, \pi_2\rangle \\
&= \mathtt{app} \circ (f \times \mathtt{Id}_A)
\end{aligned}
$$

Hence, by the fact that $\mathtt{cur}(f)$ is unique in a cartesian closed category,

$$
[\![\Phi \mid \Gamma \vdash \lambda x\colon A.(v\ x) : A \to B]\!] = f = [\![\Phi \mid \Gamma \vdash v\colon A \to B]\!] \tag{10.10}
$$

Case Eq-If-True: Let

$$
\begin{aligned}
f &= [\![\Phi \mid \Gamma \vdash v_1\colon A]\!] \\
g &= [\![\Phi \mid \Gamma \vdash v_2\colon A]\!]
\end{aligned}
$$

Then

$$
\begin{aligned}
[\![\Phi \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : A]\!] &= \mathtt{app} \circ (([\mathtt{cur}(f \circ \pi_2), \mathtt{cur}(g \circ \pi_2)] \circ \mathtt{inl} \circ \langle\rangle_\Gamma) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \\
&= \mathtt{app} \circ ((\mathtt{cur}(f \circ \pi_2) \circ \langle\rangle_\Gamma) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \\
&= \mathtt{app} \circ (\mathtt{cur}(f \circ \pi_2) \times \mathtt{Id}_\Gamma) \circ (\langle\rangle_\Gamma \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \\
&= f \circ \pi_2 \circ \langle \langle\rangle_\Gamma, \mathtt{Id}_\Gamma\rangle \\
&= f \\
&= [\![\Phi \mid \Gamma \vdash v_1\colon A]\!]
\end{aligned}
$$

Case Eq-If-False: Let

$$
\begin{aligned}
f &= [\![\Phi \mid \Gamma \vdash v_1\colon A]\!] \\
g &= [\![\Phi \mid \Gamma \vdash v_2\colon A]\!]
\end{aligned}
$$

Then

$$
\begin{aligned}
[\![\Phi \mid \Gamma \vdash \mathtt{if}_A\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 : A]\!] &= \mathtt{app} \circ (([\mathtt{cur}(f \circ \pi_2), \mathtt{cur}(g \circ \pi_2)] \circ \mathtt{inr} \circ \langle\rangle_\Gamma) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \\
&= \mathtt{app} \circ ((\mathtt{cur}(g \circ \pi_2) \circ \langle\rangle_\Gamma) \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \\
&= \mathtt{app} \circ (\mathtt{cur}(g \circ \pi_2) \times \mathtt{Id}_\Gamma) \circ (\langle\rangle_\Gamma \times \mathtt{Id}_\Gamma) \circ \delta_\Gamma \\
&= g \circ \pi_2 \circ \langle \langle\rangle_\Gamma, \mathtt{Id}_\Gamma\rangle \\
&= g \\
&= [\![\Phi \mid \Gamma \vdash v_2\colon A]\!]
\end{aligned}
$$

Case Eq-If-Eta: Let

$$\begin{aligned} f &= [\![\Phi \mid \Gamma \vdash v_1 \colon \texttt{Bool}]\!] \\ g &= [\![\Phi \mid \Gamma, x : \texttt{Bool} \vdash v_2 \colon A]\!] \end{aligned}$$

Then by the substitution theorem,

$$\begin{aligned} [\![\Phi \mid \Gamma \vdash v_2[\texttt{true}/x] \colon A]\!] &= g \circ \langle \texttt{Id}_\Gamma, \texttt{inl}_1 \circ \langle\rangle_\Gamma \rangle \\ [\![\Phi \mid \Gamma \vdash v_2[\texttt{false}/x] \colon A]\!] &= g \circ \langle \texttt{Id}_\Gamma, \texttt{inr}_1 \circ \langle\rangle_\Gamma \rangle \\ [\![\Phi \mid \Gamma \vdash v_2[v_1/x] \colon A]\!] &= g \circ \langle \texttt{Id}_\Gamma, f \rangle \end{aligned}$$

Hence we have (Using the diagonal and twist morphisms):

$$\begin{aligned}
&[\![\Phi \mid \Gamma \vdash \texttt{if}_A\ v_1\ \texttt{then}\ v_2[\texttt{true}/x]\ \texttt{else}\ v_2[\texttt{false}/x] : A]\!] \\
&= \texttt{app} \circ (([\texttt{cur}(g \circ \langle \texttt{Id}_\Gamma, \texttt{inl}_1 \circ \langle\rangle_\Gamma \rangle \circ \pi_2), \texttt{cur}(g \circ \langle \texttt{Id}_\Gamma, \texttt{inr}_1 \circ \langle\rangle_\Gamma \rangle \circ \pi_2)] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \\
&= \texttt{app} \circ (([\texttt{cur}(g \circ \langle \pi_2, \texttt{inl}_1 \circ \langle\rangle_\Gamma \circ \pi_2 \rangle), \texttt{cur}(g \circ \langle \pi_2, \texttt{inr}_1 \circ \langle\rangle_\Gamma \circ \pi_2 \rangle)] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Pairing property} \\
&= \texttt{app} \circ (([\texttt{cur}(g \circ \langle \pi_2, \texttt{inl}_1 \circ \langle\rangle_\Gamma \circ \pi_1 \rangle), \texttt{cur}(g \circ \langle \pi_2, \texttt{inr}_1 \circ \langle\rangle_\Gamma \circ \pi_1 \rangle)] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Terminal is unique} \\
&= \texttt{app} \circ (([\texttt{cur}(g \circ (\texttt{Id}_\Gamma \times (\texttt{inl}_1 \circ \langle\rangle_1)) \circ \tau_{1,\Gamma}), \texttt{cur}(g \circ (\texttt{Id}_\Gamma \times (\texttt{inr}_1 \circ \langle\rangle_1)) \circ \tau_{1,\Gamma})] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Twist definition} \\
&= \texttt{app} \circ (([\texttt{cur}(g \circ (\texttt{Id}_\Gamma \times \texttt{inl}_1) \circ \tau_{1,\Gamma}), \texttt{cur}(g \circ (\texttt{Id}_\Gamma \times \texttt{inr}_1) \circ \tau_{1,\Gamma})] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Identity} = \texttt{Id}_1 \\
&= \texttt{app} \circ (([\texttt{cur}(g \circ \tau_{1+1,\Gamma} \circ (\texttt{inl}_1 \times \texttt{Id}_\Gamma)), \texttt{cur}(g \circ \tau_{1+1,\Gamma} \circ (\texttt{inr}_1 \times \texttt{Id}_\Gamma))] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Twist commutivity} \\
&= \texttt{app} \circ (([\texttt{cur}(g \circ \tau_{1+1,\Gamma}) \circ \texttt{inl}_1, \texttt{cur}(g \circ \tau_{1+1,\Gamma}) \circ \texttt{inr}_1] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Exponential property} \\
&= \texttt{app} \circ ((\texttt{cur}(g \circ \tau_{1+1,\Gamma}) \circ [\texttt{inl}_1, \texttt{inr}_1] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Factoring out } \texttt{cur}(..) \\
&= \texttt{app} \circ ((\texttt{cur}(g \circ \tau_{1+1,\Gamma}) \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Since } [\texttt{inl}, \texttt{inr}] \text{ is the identity} \\
&= \texttt{app} \circ (\texttt{cur}(g \circ \tau_{1+1,\Gamma}) \times \texttt{Id}_\Gamma) \circ (f \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Factoring} \\
&= g \circ \tau_{1+1,\Gamma} \circ (f \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \quad \text{Definition of } \texttt{app}, \texttt{cur}(..) \\
&= g \circ (\texttt{Id}_\Gamma \times f) \circ \tau_{\Gamma,\Gamma} \circ \delta_\Gamma \quad \text{Twist commutivity} \\
&= g \circ (\texttt{Id}_\Gamma \times f) \circ \langle \texttt{Id}_\Gamma, \texttt{Id}_\Gamma \rangle \quad \text{Twist, diagonal defintions} \\
&= g \circ \langle \texttt{Id}_\Gamma, f \rangle \\
&= [\![\Phi \mid \Gamma \vdash v_2[v_1/x] \colon A]\!]
\end{aligned}$$

Case Eq-Effect-Beta: let

$$\begin{aligned} h &= [\![\Phi \vdash \epsilon \colon \texttt{Effect}]\!] \\ f &= [\![\Phi, \alpha \mid \Gamma \vdash v \colon A]\!] \\ A &= [\![\Phi, \alpha \vdash A[\alpha/\alpha] \colon \texttt{Type}]\!] \end{aligned}$$

Then

$$[\![\Phi \mid \Gamma \vdash \Lambda\alpha.v \colon \forall\alpha.A]\!] = \overline{f} \tag{10.11}$$

So

$$\begin{aligned} [\![\Phi \mid \Gamma \vdash (\Lambda\alpha.v)\ \epsilon \colon \forall\alpha.A]\!] &= \langle \texttt{Id}_I, h\rangle^*(\epsilon_A) \circ \overline{f} \\ &= \langle \texttt{Id}_I, h\rangle^*(\epsilon_A) \circ \langle \texttt{Id}_I, h\rangle^*(\pi_1^*(\overline{f})) \quad \text{Identity functor} \\ &= \langle \texttt{Id}_I, h\rangle^*(\epsilon_A \circ \pi_1^*(\overline{f})) \\ &= \langle \texttt{Id}_I, h\rangle^*(f) \quad \text{By adjunction} \\ &= [\![\Phi \mid \Gamma \vdash v[\epsilon/\alpha] \colon A[e/\alpha]]\!] \quad \text{By substitution theorem} \end{aligned}$$

Case Eq-Effect-Eta: Let

$$f = [\![\Phi \mid \Gamma \vdash v\colon \forall\alpha.A]\!]$$
$$A = [\![\Phi, \alpha \vdash A\colon \mathtt{Type}]\!]$$

so

$$\begin{aligned}
[\![\Phi \mid \Gamma \vdash \Lambda\alpha.(v\ \alpha)\colon \forall\alpha.A]\!] &= \overline{[\![\Phi, \alpha \mid \Gamma \vdash v\ \alpha\colon A]\!]} \\
&= \overline{\langle \mathtt{Id}_{I\times U}, \pi_2\rangle^*(\epsilon_{[\![\Phi,\alpha,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]}) \circ \pi_1^*(f)}
\end{aligned}$$

Let's look at $[\![\Phi, \alpha, \beta \vdash A[B/\alpha]\colon \mathtt{Type}]\!]$.

We have the weakening:

$$\iota\pi\times\colon \Phi, \alpha, \beta \rhd \Phi, \beta \tag{10.12}$$

So by the weakening theorem on type denotations:

$$\begin{aligned}
[\![\Phi, \alpha, \beta \vdash A[\beta/\alpha]\colon \mathtt{Type}]\!] &= (\pi_1 \times \mathtt{Id}_U)^*[\![\Phi, \beta \vdash A[\beta/\alpha]\colon \mathtt{Type}]\!] \\
\forall_{I\times U}([\![\Phi, \alpha, \beta \vdash A[\beta/\alpha]\colon \mathtt{Type}]\!]) &= \forall_I(\pi_1 \times \mathtt{Id}_U)^*([\![\Phi, \beta \vdash A[\beta/\alpha]\colon \mathtt{Type}]\!]) \\
&= \pi_1^*\forall_I([\![\Phi, \beta \vdash A[\beta/\alpha]\colon \mathtt{Type}]\!]) \\
\epsilon_{[\![\Phi,\alpha,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]} &= \widehat{\mathtt{Id}_{\pi_1^*\forall_I([\![\Phi,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!])}} \\
&= \widehat{\mathtt{Id}_{\pi_1^*\forall_I A}} \\
&= \widehat{\pi_1^*(\mathtt{Id}_{\forall_I A})} \\
&= \widehat{\pi_1^*(\overline{\epsilon_A})} \\
&= \widehat{\overline{(\pi_1 \times \mathtt{Id}_U)^*(\epsilon_A)}} \\
&= (\pi_1 \times \mathtt{Id}_U)^*(\epsilon_A)
\end{aligned}$$

So

$$\begin{aligned}
[\![\Phi \mid \Gamma \vdash \Lambda\alpha.(v\ \alpha)\colon \forall\alpha.A]\!] &= \overline{\langle \mathtt{Id}_{I\times U}, \pi_2\rangle^*(\epsilon_{[\![\Phi,\alpha,\beta\vdash A[\beta/\alpha]:\mathtt{Type}]\!]}) \circ \pi_1^*(f)} \\
&= \overline{\langle \mathtt{Id}_{I\times U}, \pi_2\rangle^*((\pi_1 \times \mathtt{Id}_U)^*(\epsilon_A)) \circ \pi_1^*(f)} \\
&= \overline{\langle \pi_1, \pi_2\rangle^*(\epsilon_A) \circ \pi_1^*(f)} \\
&= \overline{\mathtt{Id}_{I\times U}^*(\epsilon_A) \circ \pi_1^*(f)} \\
&= \overline{\epsilon_A \circ \pi_1^*(f)} \quad \text{By adjunction} \\
&= f
\end{aligned}$$

10.2.3 Congruences

These cases can be proved fairly mechanically by assuming the preconditions, using induction to prove that the matching pairs of Subexpressions have equal denotations, then constructing the denotations of the expressions using the equal denotations which gives trivially equal denotations.

Case Eq-Fn: By inversion, we have $\Phi \mid \Gamma, x\colon A \vdash v_1 \approx v_2\colon B$ By induction, we therefore have $[\![\Phi \mid \Gamma, x\colon A \vdash v_1\colon B]\!] = [\![\Phi \mid \Gamma, x\colon A \vdash v_2\colon B]\!]$

Then let

$$f = [\![\Phi \mid \Gamma, x\colon A \vdash v_1\colon B]\!] = [\![\Phi \mid \Gamma, x\colon A \vdash v_2\colon B]\!] \tag{10.13}$$

And so

$$[\![\Phi \mid \Gamma \vdash \lambda x\colon A.v_1 : A \to B]\!] = \mathtt{cur}(f) = [\![\Phi \mid \Gamma \vdash \lambda x\colon A.v_2 : A \to B]\!] \tag{10.14}$$

Case Eq-Return: By inversion, we have $\Phi \mid \Gamma \vdash v_1 \approx v_2\colon A$ By induction, we therefore have $[\![\Phi \mid \Gamma \vdash v_1\colon A]\!] = [\![\Phi \mid \Gamma \vdash v_2\colon A]\!]$

Then let

$$f = [\![\Phi \mid \Gamma \vdash v_1\colon A]\!] = [\![\Phi \mid \Gamma \vdash v_2\colon A]\!] \tag{10.15}$$

And so

$$[\![\Phi \mid \Gamma \vdash \mathtt{return}\, v_1 : \mathtt{M}_{\mathtt{1}} A]\!] = \eta_A \circ f = [\![\Phi \mid \Gamma \vdash \mathtt{return}\, v_2 : \mathtt{M}_{\mathtt{1}} A]\!] \tag{10.16}$$

Case Eq-Apply: By inversion, we have $\Phi \mid \Gamma \vdash v_1 \approx v_1'\colon A \to B$ and $\Phi \mid \Gamma \vdash v_2 \approx v_2'\colon A$ By induction, we therefore have $[\![\Phi \mid \Gamma \vdash v_1\colon A \to B]\!] = [\![\Phi \mid \Gamma \vdash v_1'\colon A \to B]\!]$ and $[\![\Phi \mid \Gamma \vdash v_2\colon A]\!] = [\![\Phi \mid \Gamma \vdash v_2'\colon A]\!]$

Then let

$$\begin{aligned} f &= [\![\Phi \mid \Gamma \vdash v_1\colon A \to B]\!] = [\![\Phi \mid \Gamma \vdash v_1'\colon A \to B]\!] \\ g &= [\![\Phi \mid \Gamma \vdash v_2\colon A]\!] = [\![\Phi \mid \Gamma \vdash v_2'\colon A]\!] \end{aligned}$$

And so

$$[\![\Phi \mid \Gamma \vdash v_1\ v_2\colon B]\!] = \mathtt{app} \circ \langle f, g\rangle = [\![\Phi \mid \Gamma \vdash v_1'\ v_2'\colon B]\!] \tag{10.17}$$

Case Eq-Bind: By inversion, we have $\Phi \mid \Gamma \vdash v_1 \approx v_1'\colon \mathtt{M}_{\epsilon_1} A$ and $\Phi \mid \Gamma, x\colon A \vdash v_2 \approx v_2'\colon \mathtt{M}_{\epsilon_2} B$ By induction, we therefore have $[\![\Phi \mid \Gamma \vdash v_1\colon \mathtt{M}_{\epsilon_1} A]\!] = [\![\Phi \mid \Gamma \vdash v_1'\colon \mathtt{M}_{\epsilon_1} A]\!]$ and $[\![\Phi \mid \Gamma, x\colon A \vdash v_2\colon \mathtt{M}_{\epsilon_2} B]\!] = [\![\Phi \mid \Gamma, x\colon A \vdash v_2'\colon \mathtt{M}_{\epsilon_2} B]\!]$

Then let

$$\begin{aligned} f &= [\![\Phi \mid \Gamma \vdash v_1\colon \mathtt{M}_{\epsilon_1} A]\!] = [\![\Phi \mid \Gamma \vdash v_1'\colon \mathtt{M}_{\epsilon_1} A]\!] \\ g &= [\![\Phi \mid \Gamma, x\colon A \vdash v_2\colon \mathtt{M}_{\epsilon_2} B]\!] = [\![\Phi \mid \Gamma, x\colon A \vdash v_2'\colon \mathtt{M}_{\epsilon_2} B]\!] \end{aligned}$$

And so

$$\begin{aligned} [\![\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} A]\!] &= \mu_{\epsilon_1, \epsilon_2, B} \circ T_{\epsilon_1} g \circ \mathtt{t}_{\epsilon_1, \Gamma, A} \circ \langle \mathtt{Id}_\Gamma, f\rangle \\ &= [\![\Phi \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} A]\!] \end{aligned}$$

Case Eq-If: By inversion, we have $\Phi \mid \Gamma \vdash v \approx v'\colon \mathtt{Bool}$, $\Phi \mid \Gamma \vdash v_1 \approx v_1'\colon A$ and $\Phi \mid \Gamma \vdash v_2 \approx v_2'\colon A$ By induction, we therefore have $[\![\Phi \mid \Gamma \vdash v\colon \mathtt{Bool}]\!] = [\![\Phi \mid \Gamma \vdash v'\colon \mathtt{Bool}]\!]$, $[\![\Phi \mid \Gamma \vdash v_1\colon A]\!] = [\![\Phi \mid \Gamma \vdash v_1'\colon A]\!]$ and $[\![\Phi \mid \Gamma, x\colon A \vdash v_2\colon A]\!] = [\![\Phi \mid \Gamma, x\colon A \vdash v_2'\colon A]\!]$

Then let

$$\begin{aligned} f &= [\![\Phi \mid \Gamma \vdash v\colon \mathtt{Bool}]\!] = [\![\Phi \mid \Gamma \vdash v'\colon \mathtt{Bool}]\!] \\ g &= [\![\Phi \mid \Gamma \vdash v_1\colon A]\!] = [\![\Phi \mid \Gamma \vdash v_1'\colon A]\!] \\ h &= [\![\Phi \mid \Gamma, x\colon A \vdash v_2\colon A]\!] = [\![\Phi \mid \Gamma, x\colon A \vdash v_2'\colon A]\!] \end{aligned}$$

And so

$$\begin{aligned}\llbracket \Phi \mid \Gamma \vdash \texttt{if}_A\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2 : A \rrbracket &= \texttt{app} \circ (([\texttt{cur}(g \circ \pi_2), \texttt{cur}(h \circ \pi_2)] \circ f) \times \texttt{Id}_\Gamma) \circ \delta_\Gamma \\ &= \llbracket \Phi \mid \Gamma \vdash \texttt{if}_A\ v'\ \texttt{then}\ v_1'\ \texttt{else}\ v_2' : A \rrbracket\end{aligned}$$

Case Eq-Subtype: By inversion, we have $\Phi \mid \Gamma \vdash v_1 \approx v_2 \colon A$, and $A \leq :_\Phi B$ By induction, we therefore have $\llbracket \Phi \mid \Gamma \vdash v_1 \colon A \rrbracket = \llbracket \Phi \mid \Gamma \vdash v_2 \colon A \rrbracket$

Then let

$$\begin{aligned}f &= \llbracket \Phi \mid \Gamma \vdash v_1 \colon A \rrbracket = \llbracket \Phi \mid \Gamma \vdash v_2 \colon B \rrbracket \\ g &= \llbracket A \leq :_\Phi B \rrbracket\end{aligned}$$

And so

$$\llbracket \Phi \mid \Gamma \vdash v_1 \colon B \rrbracket = g \circ f = \llbracket \Phi \mid \Gamma \vdash v_1 \colon B \rrbracket \tag{10.18}$$

Case Eq-Effect-Gen: By inversion, we have $\Phi, \alpha \mid \Gamma \vdash v_1 \approx v_2 \colon A$. So by induction, $\llbracket \Phi, \alpha \mid \Gamma \vdash v_1 \colon A \rrbracket = \llbracket \Phi, \alpha \mid \Gamma \vdash v_2 \colon A \rrbracket$

So

$$\begin{aligned}\llbracket \Phi \mid \Gamma \vdash \Lambda\alpha.v_1 \colon \forall\alpha.A \rrbracket &= \overline{\llbracket \Phi, \alpha \mid \Gamma \vdash v_1 \colon A \rrbracket} \\ &= \overline{\llbracket \Phi, \alpha \mid \Gamma \vdash v_2 \colon A \rrbracket} \\ &= \llbracket \Phi \mid \Gamma \vdash \Lambda\alpha.v_2 \colon \forall\alpha.A \rrbracket\end{aligned}$$

Case Eq-Effect-Spec: By inversion, we have $\Phi \mid \Gamma \vdash v_1 \approx v_2 \colon \forall\alpha.A$ and $\Phi \vdash \epsilon \colon \texttt{Effect}$.

So by induction, we have $\llbracket \Phi \mid \Gamma \vdash v_1 \colon \forall\alpha.A \rrbracket = \llbracket \Phi \mid \Gamma \vdash v_2 \colon \forall\alpha.A \rrbracket$

So

$$\begin{aligned}\llbracket \Phi \mid \Gamma \vdash v_1\ \epsilon \colon A[\epsilon/\alpha] \rrbracket &= \langle \texttt{Id}_I, \llbracket \Phi \vdash \epsilon \colon \texttt{Effect} \rrbracket \rangle^*(\epsilon_A) \circ \llbracket \Phi \mid \Gamma \vdash v_1 \colon \forall\alpha.A \rrbracket \\ &= \langle \texttt{Id}_I, \llbracket \Phi \vdash \epsilon \colon \texttt{Effect} \rrbracket \rangle^*(\epsilon_A) \circ \llbracket \Phi \mid \Gamma \vdash v_2 \colon \forall\alpha.A \rrbracket \\ &= \llbracket \Phi \mid \Gamma \vdash v_2\ \epsilon \colon A[\epsilon/\alpha] \rrbracket\end{aligned}$$

$\square$