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Chapter 1

Language Definition

1.1 Terms

Making the language no-longer differentiate between values and computations.

1.1.1 Value Terms

$$\begin{aligned} v ::= & x \\ & \mid \lambda x : A.v \\ & \mid \mathtt{C}^{A} \\ & \mid \mathtt{()} \\ & \mid \mathtt{true} \mid \mathtt{false} \\ & \mid \Lambda\alpha.v \\ & \mid v\ \epsilon \\ & \mid \mathtt{if}_{A,}\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 \\ & \mid v_1\ v_2 \\ & \mid \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 \\ & \mid \mathtt{return} v \end{aligned} \tag{1.1}$$

1.2 Type System

1.2.1 Ground Effects

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

1.2.2 Effect Po-Monoid Under a Effect Environment

Derive a new Po-Monoid for each Φ:

$$(E_\Phi, \cdot_\Phi, \mathtt{1}, \leq_\Phi) \tag{1.2}$$

Where meta-variables, ϵ, range over E_Φ Where

$$E_\Phi = E \cup \{\alpha \mid \alpha \in \Phi\} \tag{1.3}$$

And

$$()\frac{\epsilon_3 = \epsilon_1 \cdot \epsilon_2}{\epsilon_3 = \epsilon_1 \cdot_\Phi \epsilon_2} \tag{1.4}$$

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

$$\epsilon_1 \leq_\Phi \epsilon_2 \Leftrightarrow \forall \sigma\downarrow . \epsilon_1 [\sigma \downarrow] \leq \epsilon_2 [\sigma \downarrow] \tag{1.5}$$

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

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

1.2.4 Sub-typing

There exists a sub-typing pre-order relation $\leq:_\gamma$ over ground types that is:

- (Reflexive)$\frac{}{A \leq:_\gamma A}$
- (Transitive)$\frac{A \leq:_\gamma B \quad B \leq:_\gamma C}{A \leq:_\gamma C}$

We extend this relation with the function and effect-lambda sub-typing rules to yield the full sub-typing relation $\leq:$

- (ground)$\frac{A \leq:_\gamma B}{A \leq: B}$
- (Fn)$\frac{A \leq: A' \quad B' \leq: B}{A' \rightarrow B' \leq: A \rightarrow B}$
- (All)$\frac{A \leq: A'}{\forall \alpha . A \leq: \forall a . A'}$
- (Effect)$\frac{A \leq: B \quad \epsilon_1 \leq \epsilon_2}{\mathtt{M}_{\epsilon_1} A \leq: \mathtt{M}_{\epsilon_2} B}$

1.2.5 Type and Effect Environments

A type environment is a snoc-list of tern-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

- (Atom)$\frac{}{\diamond \mathtt{Ok}}$
- (A)$\frac{\Phi \mathtt{Ok} \quad \alpha \notin \Phi}{\Phi, \alpha \mathtt{Ok}}$

Well-Formed-ness of effects We define a relation $\Phi \vdash \epsilon$.

- (Ground) $\frac{\Phi \mathtt{Ok}}{\Phi \vdash e}$
- (Var) $\frac{\Phi, \alpha \mathtt{Ok}}{\Phi, \alpha \vdash \alpha}$
- (Weaken) $\frac{\Phi \vdash \alpha}{\Phi, \beta \vdash \alpha}$ (if $\alpha \neq \beta$)
- (Monoid Op) $\frac{\Phi \vdash \epsilon_1 \quad \Phi \vdash \epsilon_2}{\Phi \vdash \epsilon_1 \cdot \epsilon_2}$

Well-Formed-ness of Types We define a relation $\Phi \vdash \tau$ on types.

- (Ground) $\frac{}{\Phi \vdash \gamma}$
- (Lambda) $\frac{\Phi \vdash A \quad \Phi \vdash B}{\Phi \vdash A \to B}$
- (Computation) $\frac{\Phi \vdash A \quad \Phi \vdash \epsilon}{\Phi \vdash \mathtt{M}_\epsilon A}$
- (For-All) $\frac{\Phi, \alpha \vdash A}{\Phi \vdash \forall \alpha . A}$

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

- (Nil) $\frac{}{\Phi \vdash \diamond \mathtt{Ok}}$
- (Var) $\frac{\Phi \vdash \Gamma \mathtt{Ok} \quad x \notin \mathtt{dom}(\Gamma) \quad \Phi \vdash A}{\Phi \vdash \Gamma, x : A \mathtt{Ok}}$

1.2.6 Type Rules

- (Const) $\frac{\Phi \vdash \Gamma \mathtt{Ok} \quad \Phi \vdash A}{\Phi | \Gamma \vdash \mathtt{C}^A : A}$
- (Unit) $\frac{\Phi \vdash \Gamma \mathtt{Ok}}{\Phi | \Gamma \vdash \mathtt{()} : \mathtt{Unit}}$
- (True) $\frac{\Phi \vdash \Gamma \mathtt{Ok}}{\Phi | \Gamma \vdash \mathtt{true} : \mathtt{Bool}}$
- (False) $\frac{\Phi \vdash \Gamma \mathtt{Ok}}{\Phi | \Gamma \vdash \mathtt{false} : \mathtt{Bool}}$
- (Var) $\frac{\Phi \vdash \Gamma, x : A \mathtt{Ok}}{\Phi | \Gamma, x : A \vdash x : A}$
- (Weaken) $\frac{\Phi | \Gamma \vdash x : A \quad \Phi \vdash B}{\Phi | \Gamma, y : B \vdash x : A}$ (if $x \neq y$)
- (Fn) $\frac{\Phi | \Gamma, x : A \vdash v : \beta}{\Phi | \Gamma \vdash \lambda x : A . v : A \to B}$
- (Sub) $\frac{\Phi | \Gamma \vdash v : A \quad A \leq : B}{\Phi | \Gamma \vdash v : B}$
- (Effect-Abs) $\frac{\Phi, \alpha | \Gamma \vdash v : A}{\Phi | \Gamma \vdash \Lambda \alpha . v : \forall \alpha . A}$
- (Effect-apply) $\frac{\Phi | \Gamma \vdash v : \forall \alpha . A \quad \Phi \vdash \epsilon}{\Phi | \Gamma \vdash v \ \epsilon : A[\epsilon / \alpha]}$
- (Return) $\frac{\Phi | \Gamma \vdash v : A}{\Phi | \Gamma \vdash \mathtt{return} v : \mathtt{M}_{\mathtt{1}} A}$
- (Apply) $\frac{\Phi | \Gamma \vdash v_1 : A \to \mathtt{M}_\epsilon B \quad \Phi | \Gamma \vdash v_2 : A}{\Phi | \Gamma \vdash v_1 \ v_2 : \mathtt{M}_\epsilon B}$
- (If) $\frac{\Phi | \Gamma \vdash v : \mathtt{Bool} \quad \Phi | \Gamma \vdash v_1 : A \quad \Phi | \Gamma \vdash v_2 : A}{\Phi | \Gamma \vdash \mathtt{if}_{A,} \ V \ \mathtt{then} \ v_1 \ \mathtt{else} \ v_2 : A}$
- (Do) $\frac{\Phi | \Gamma \vdash v_1 : \mathtt{M}_{\epsilon_1} A \quad \Phi | \Gamma, x : A \vdash v_2 : \mathtt{M}_{\epsilon_2} B}{\Phi | \Gamma \vdash \mathtt{do} \ x \leftarrow v_1 \ \mathtt{in} \ v_2 : \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B}$

1.2.7 Ok Lemma

If $\Phi \mid \Gamma \vdash t\colon \tau$ then $\Phi \vdash \Gamma \texttt{Ok}$.

Proof If $\Gamma, x : A\texttt{Ok}$ 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

Category Requirements

2.1 CCC

The section should be a cartesian closed category. That is it should have:

- A Terminal object $\mathtt{1}$
- Binary products
- Exponentials

Further more, it should have a co-product of the terminal object $\mathtt{1}$. This is required for the beta-eta equivalence of `if-then-else` terms.

$\mathtt{1} \xrightarrow{inl} A \xleftarrow{inr} \mathtt{1}$

For each:

$\mathtt{1} \xrightarrow{f} A \xleftarrow{g} \mathtt{1}$

There exists unique $[f, g] : \mathtt{1} + \mathtt{1} \to A$ such that:

$$\begin{tikzcd}
 & A & \\
\mathtt{1} \arrow[ur, "f"] \arrow[r, "\mathtt{inl}"'] & \mathtt{1} + \mathtt{1} \arrow[u, "{[f,g]}"] & \mathtt{1} \arrow[ul, "g"'] \arrow[l, "\mathtt{inr}"]
\end{tikzcd}$$

2.2 Graded Pre-Monad

The category should have a graded pre-monad. That is:

- An endo-functor indexed by the po-monad on effects: $T : (\mathbb{E}, \cdot\, \mathtt{1}, \leq) \to \mathtt{Cat}(\mathbb{C}, \mathbb{C})$
- A unit natural transformation: $\eta : \mathtt{Id} \to T_{\mathtt{1}}$
- A join natural transformation: $\mu_{\epsilon_1, \epsilon_2,} : T_{\epsilon_1} T_{\epsilon_2} \to T_{\epsilon_1 \cdot \epsilon_2}$

Subject to the following commutative diagrams:

2.2.1 Left Unit

$$\begin{tikzcd}
T_\epsilon A \arrow[r, "T_\epsilon \eta_A"] \arrow[dr, "\mathtt{Id}_{T_\epsilon A}"] & T_\epsilon T_{\mathtt{1}} A \arrow[d, "\mu_{\epsilon, \mathtt{1}, A}"] \\
 & T_\epsilon A
\end{tikzcd}$$

2.2.2 Right Unit

$$\begin{tikzcd}
T_\epsilon A \arrow[r, "\eta_{T_\epsilon A}"] \arrow[dr, "\mathtt{Id}_{T_\epsilon A}"] & T_{\mathtt{1}} T_{\mathtt{1}} A \arrow[d, "\mu_{\mathtt{1},\epsilon,A}"] \\
& T_\epsilon A
\end{tikzcd}$$

2.2.3 Associativity

$$\begin{tikzcd}
T_{\epsilon_1} T_{\epsilon_2} T_{\epsilon_3} A \arrow[r, "\mu_{\epsilon_1,\epsilon_2,T_{\epsilon_3} A}"] \arrow[d, "T_{\epsilon_1} \mu_{\epsilon_2,\epsilon_3,A}"] & T_{\epsilon_1 \cdot \epsilon_2} T_{\epsilon_3} A \arrow[d, "\mu_{\epsilon_1 \cdot \epsilon_2,\epsilon_3,A}"] \\
T_{\epsilon_1} T_{\epsilon_2 \cdot \epsilon_3} A \arrow[r, "\mu_{\epsilon_1,\epsilon_2 \cdot \epsilon_3,A}"] & T_{\epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3} A
\end{tikzcd}$$

2.3 Tensor Strength

The category should also have tensorial strength over its products and monads. That is, it should have a natural transformation

$$\mathtt{t}_{\epsilon,A,B} : A \times T_\epsilon B \to T_\epsilon(A \times B)$$

Satisfying the following rules:

2.3.1 Left Naturality

$$\begin{tikzcd}
A \times T_\epsilon B \arrow[r, "\mathtt{Id}_A \times T_\epsilon f"] \arrow[d, "\mathtt{t}_{\epsilon,A,B}"] & A \times T_\epsilon B' \arrow[d, "\mathtt{t}_{\epsilon,A,B'}"] \\
T_\epsilon(A \times B) \arrow[r, "T_\epsilon(\mathtt{Id}_A \times f)"] & T_\epsilon(A \times B')
\end{tikzcd}$$

2.3.2 Right Naturality

$$\begin{tikzcd}
A \times T_\epsilon B \arrow[r, "f \times \mathtt{Id}_{T_\epsilon B}"] \arrow[d, "\mathtt{t}_{\epsilon,A,B}"] & A' \times T_\epsilon B \arrow[d, "\mathtt{t}_{\epsilon,A',B}"] \\
T_\epsilon(A \times B) \arrow[r, "T_\epsilon(f \times \mathtt{Id}_B)"] & T_\epsilon(A' \times B)
\end{tikzcd}$$

2.3.3 Unitor Law

$$\begin{tikzcd}
\mathtt{1} \times T_\epsilon A \arrow[r, "\mathtt{t}_{\epsilon,\mathtt{1},A}"] \arrow[dr, "\lambda_{T_\epsilon A}"] & T_\epsilon(\mathtt{1} \times A) \arrow[d, "T_\epsilon(\lambda_A)"] \\
& T_\epsilon A
\end{tikzcd}$$

Where $\lambda : \mathtt{1} \times \mathtt{Id} \to \mathtt{Id}$ is the left-unitor. $(\lambda = \pi_2)$

Tensor Strength and Projection Due to the left-unitor law, we can develop a new law for the commutivity of π_2 with $\mathtt{t}_{,,}$

$$\pi_{2,A,B} = \pi_{2,\mathtt{1},B} \circ (\langle\rangle_A \times \mathtt{Id}_B)$$

And $\pi_{2,\mathtt{1}}$ is the left unitor, so by tensorial strength:

$$
\begin{aligned}
T_\epsilon \pi_2 \circ \mathtt{t}_{\epsilon,A,B} &= T_\epsilon \pi_{2,\mathtt{1},B} \circ T_\epsilon(\langle\rangle_A \times \mathtt{Id}_B) \circ \mathtt{t}_{\epsilon,A,B} \\
&= T_\epsilon \pi_{2,1,B} \circ \mathtt{t}_{\epsilon,\mathtt{1},B} \circ (\langle\rangle_A \times \mathtt{Id}_B) \\
&= \pi_{2,1,B} \circ (\langle\rangle_A \times \mathtt{Id}_B) \\
&= \pi_2
\end{aligned}
\tag{2.1}
$$

So the following commutes:

$$\begin{tikzcd}
A \times T_\epsilon B \arrow[r, "\mathtt{t}_{\epsilon,A,B}"] \arrow[dr, "\pi_2"] & T_\epsilon(A \times B) \arrow[d, "T_\epsilon \pi_2"] \\
& T_\epsilon B
\end{tikzcd}$$

2.3.4 Commutativity with Join

$$\begin{tikzcd}
A \times T_{\epsilon_1} T_{\epsilon_2} B \arrow[r, "\mathtt{t}_{\epsilon_1,A,T_{\epsilon_2}B}"] \arrow[dr, "\mathtt{Id}_A \times \mu_{\epsilon_1,\epsilon_2,B}"] & T_{\epsilon_1}(A \times T_{\epsilon_2} B) \arrow[r, "T_{\epsilon_1}\mathtt{t}_{\epsilon_2,A,B}"] & T_{\epsilon_1} T_{\epsilon_2}(A \times B) \arrow[d, "\mu_{\epsilon_1,\epsilon_2,A\times B}"] \\
& A \times T_{\epsilon_1 \cdot \epsilon_2} B \arrow[r, "\mathtt{t}_{\epsilon_1 \cdot \epsilon_2,A,B}"] & T_{\epsilon_1 \cdot \epsilon_2}(A \times B)
\end{tikzcd}$$

2.4 Commutivity with Unit

$$\begin{tikzcd}
A \times B \arrow[r, "\mathtt{Id}_A \times \eta_B"] \arrow[dr, "\eta_{A\times B}"] & A \times T_\epsilon B \arrow[d, "\mathtt{t}_{\epsilon,A,B}"] \\
& T_\epsilon(A \times B)
\end{tikzcd}$$

2.5 Commutivity with α

Let $\alpha_{A,B,C} = \langle \pi_1 \circ \pi_1, \langle \pi_2 \circ \pi_1, \pi_2 \rangle \rangle : ((A \times B) \times C) \to (A \times (B \times C))$

$$\begin{tikzcd}
(A \times B) \times T_\epsilon C \arrow[rr, "\mathtt{t}_{\epsilon,(A\times B),C}"] \arrow[d, "\alpha_{A,B,T_\epsilon C}"] & & T_\epsilon((A \times B) \times C) \arrow[d, "T_\epsilon \alpha_{A,B,C}"] \\
A \times (B \times T_\epsilon C) \arrow[r, "\mathtt{Id}_A \times \mathtt{t}_{\epsilon,B,C}"] & A \times T_\epsilon(B \times C) \arrow[r, "\mathtt{t}_{\epsilon,A,(B\times C)}"] & T_\epsilon(A \times (B \times C))
\end{tikzcd}$$

TODO: Needed?

2.6 Subeffecting

For each instance of the pre-order $(\mathbb{E}, \leq)$, $\epsilon_1 \leq \epsilon_2$, there exists a natural transformation $[\![\epsilon_1 \leq \epsilon_2]\!] : T_{\epsilon_1} \to T_{\epsilon_2}$ that commutes with $\mathtt{t}_{,,}$:

2.6.1 Subeffecting and Tensor Strength

$$\begin{tikzcd}
A \times T_{\epsilon_1} B \arrow[r, "\mathtt{Id}_A \times [\![\epsilon_1 \leq \epsilon_2]\!]_B"] \arrow[d, "\mathtt{t}_{\epsilon_1,A,B}"] & A \times T_{\epsilon_2} B \arrow[d, "\mathtt{t}_{\epsilon_2,A,B}"] \\
T_{\epsilon_1}(A \times B) \arrow[r, "[\![\epsilon_1 \leq \epsilon_2]\!]_{A\times B}"] & T_{\epsilon_2}(A \times B)
\end{tikzcd}$$

2.6.2 Sub-effecting and Monadic Join

Since the monoid operation on effects is monotone, we can introduce the following diagram.

$$\begin{tikzcd}
T_{\epsilon_1}T_{\epsilon_2} \arrow[r, "T_{\epsilon_1}\llbracket\epsilon_2\leq\epsilon_2'\rrbracket_M"] \arrow[d, "\mu_{\epsilon_1,\epsilon_2,}"] & T_{\epsilon_1}T_{\epsilon_2'} \arrow[r, "\llbracket\epsilon_1\leq\epsilon_1'\rrbracket_{M,T_{\epsilon_2'}}"] & T_{\epsilon_1'}T_{\epsilon_2'} \arrow[d, "\mu_{\epsilon_1',\epsilon_2',}"] \\
T_{\epsilon_1\cdot\epsilon_2} \arrow[rr, "\llbracket\epsilon_1\cdot\epsilon_2\leq\epsilon_1'\epsilon_2'\rrbracket_M"] & & T_{\epsilon_1'\cdot\epsilon_2'}
\end{tikzcd}$$

2.7 Subtyping

The denotation of ground types $\llbracket\_\rrbracket_M$ is a functor from the pre-order category of ground types $(\gamma, \leq:_\gamma)$ to $\mathbb{C}$. This pre-ordered sub-category of $\mathbb{C}$ is extended with the rule for function subtyping to form a larger pre-ordered sub-category of $\mathbb{C}$.

$$\text{(Function Subtyping)}\frac{f = \llbracket A' \leq: A\rrbracket_M \quad g = \llbracket B \leq: B'\rrbracket_M \quad h = \llbracket \epsilon_1 \leq \epsilon_2\rrbracket}{rhs = \llbracket A \to \mathtt{M}_{\epsilon_1} B \leq: A' \to \mathtt{M}_{\epsilon_2} B'\rrbracket_M : (T_{\epsilon_1}B)^A \to (T_{\epsilon_2}B')^{A'}}$$

$$\begin{aligned}
rhs =&(h_{B'} \circ T_{\epsilon_1} g)^{A'} \circ (T_{\epsilon_1} B)^f \\
=&\mathtt{cur}(h_{B'} \circ T_{\epsilon_1} g \circ \mathtt{app}) \circ \mathtt{cur}(\mathtt{app} \circ (\mathtt{Id}_{T_{\epsilon_1}B^{A'}} \times f))
\end{aligned} \tag{2.2}$$

Chapter 3

Denotations

3.1 Helper Morphisms

3.1.1 Diagonal and Twist Morphisms

In the definition and proofs (Especially of the the If cases), I make use of the morphisms twist and diagonal.

$$\tau_{A,B} : (A \times B) \to (B \times A) = \langle \pi_2, \pi_1 \rangle \tag{3.1}$$

$$\delta_A : A \to (A \times A) = \langle \mathtt{Id}_A, \mathtt{Id}_A \rangle \tag{3.2}$$

3.2 Denotations of Types

3.2.1 Denotation of Ground Types

3.2.2 Denotation of Polymorphic Types

3.2.3 Denotation of Computation Type

3.2.4 Denotation of Function Types

3.2.5 Denotation of Type Environments

3.2.6 Denotation of Value Terms

3.2.7 Denotation of Computation Terms

Chapter 4

Unique Denotations

4.1 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 $\Gamma \vdash t\colon \tau$. 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.

4.2 Reduced Type Derivations are Unique

4.2.1 Variables

4.2.2 Constants

4.2.3 Value Terms

4.2.4 Computation Terms

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

4.3.1 Constants

4.3.2 Value Types

4.3.3 Computation Types

4.4 Denotations are Equivalent

Chapter 5

Weakening

5.1 Effect Weakening Definition

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

5.1.1 Relation

- (Id)$\frac{\Phi\texttt{Ok}}{\iota:\Phi\triangleright\Phi}$
- (Project)$\frac{\omega:\Phi'\triangleright\Phi}{\omega\pi:(\Phi',\alpha)\triangleright\Phi}$
- (Extend)$\frac{\omega:\Phi'\triangleright\Phi}{\omega\times:(\Phi',\alpha)\triangleright(\Phi,\alpha)}$

5.1.2 Weakening Properties

5.1.3 Effect Weakening Preserves Ok

$$\omega : \Phi' \triangleright \Phi \wedge \Phi\texttt{Ok} \Leftarrow \Phi'\texttt{Ok} \tag{5.1}$$

Proof

Case: ι

$$\Phi\texttt{Ok} \wedge \iota : \Phi \triangleright \Phi \Leftarrow \Phi\texttt{Ok}$$

Case: $\omega\pi$ By inversion,

$$\omega : \Phi' \triangleright \Phi \wedge \alpha \notin \Phi' \tag{5.2}$$

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

Case: $\omega\times$ By inversion,

$$\omega : \Phi' \triangleright \Phi \wedge \alpha \notin \Phi' \tag{5.3}$$

So

$$\begin{aligned}(\Phi, \alpha)\texttt{Ok} &\Rightarrow \Phi\texttt{Ok} && (5.4)\\ &\Rightarrow \Phi'\texttt{Ok} && (5.5)\\ &\Rightarrow (\Phi', \alpha)\texttt{Ok} && (5.6)\\ & && (5.7)\end{aligned}$$

5.1.4 Domain Lemma

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

Proof By trivial Induction.

5.1.5 Weakening Preserves Effect Well-Formed-Ness

If $\omega : \Phi' \triangleright \Phi$ then $\Phi \vdash \epsilon \implies \Phi' \vdash \epsilon$

Proof By induction over the well-formed-ness of effects

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

Case Var $\Phi = \Phi'', \alpha$
So either:

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

$$(\text{Var})\frac{\Phi''', \alpha\mathtt{Ok}}{\Phi''', \alpha \vdash \alpha} \tag{5.8}$$

Case: $\Phi' = \Phi''', \beta$ and $\beta \neq \alpha$
So $\omega = \omega'\pi$
By induction, $\omega' : \Phi''' \triangleright \Phi$ so

$$(\text{Weaken})\frac{\Phi''' \vdash \alpha}{\Phi' \vdash \alpha} \tag{5.9}$$

Case Weaken By inversion, $\Phi = \Phi'', \beta$.
So $\omega = \omega' \times$
And, $\Phi' = \Phi''', \beta$ So By inversion$\omega' : \Phi''' \triangleright \pi_1''$
So by induction

$$(\text{weak})\frac{\Phi''' \vdash \alpha}{\Phi' \vdash \alpha} \tag{5.10}$$

Case Monoid By inversion, $\Phi \vdash \epsilon_1$ and $\Phi \vdash \epsilon_2$. So by induction, $\Phi' \vdash \epsilon_1$ and $\Phi' \vdash \epsilon_2$, and so:

$$\Phi' \vdash \epsilon_1 \cdot \epsilon_2 \tag{5.11}$$

5.1.6 Weakening Preserves Type-Well-Formed-Ness

If $\omega : \Phi' \triangleright \Phi$ and $\Phi \vdash A$ then $\Phi' \vdash A$.

Proof:

Case Ground: By inversion, $\Phi\mathtt{Ok}$, hence by property 1 of weakening, $\Phi'\mathtt{Ok}$. Hence $\Phi' \vdash \gamma$.

Case Function: By inversion, $\Phi \vdash A$, $\Phi \vdash B$. So by induction $\Phi' \vdash A$, $\Phi' \vdash B$, hence,

$$\Phi' \vdash A \to B$$

Case Computation: By inversion$\Phi \vdash A$, and $\Phi \vdash \epsilon$.
So by induction and the effect-well-formed-ness theorem,
$\Phi' \vdash A$ and $\Phi' \vdash \epsilon$
So

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

Case For All: By inversion, $\Phi, \alpha \vdash A$ Picking $\alpha \notin \Phi'$ using α-conversion.
So $\omega\times : (\Phi', \alpha) \triangleright (\Phi, \alpha)$
So $(\Phi', \alpha) \vdash A$
So $\Phi \vdash \forall\alpha.A$

5.1.7 Corollary

$$\omega : \Phi' \triangleright \Phi \wedge \Phi \vdash \Gamma\mathtt{Ok} \implies \Phi' \vdash \Gamma\mathtt{Ok}$$

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

Case Var: By inversion$\Phi \vdash \Gamma\mathtt{Ok}$, $x \in \mathtt{dom}(\Gamma)$, $\Phi \vdash A$
So by induction $\Phi' \vdash \Gamma\mathtt{Ok}$, and $\pi_1' \vdash \Gamma\mathtt{Ok}$
So $\Phi' \vdash (\Gamma, x : A)\mathtt{Ok}$

5.1.8 Effect Weakening preserves Type Relations

$$\Phi \mid \Gamma \vdash v\colon A \wedge \omega : \Phi' \triangleright \Phi \implies \Phi' \mid \Gamma \vdash v\colon A \tag{5.12}$$

Proof:

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

$$(\text{Const})\frac{\Phi' \vdash \Gamma\mathtt{Ok}}{\Phi' \mid \Gamma \vdash \mathtt{C}^A\colon A} \tag{5.13}$$

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

$$\Phi' \mid \Gamma \vdash \lambda x : A.v\colon A \to B \tag{5.14}$$

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

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

$$\Phi' \mid \Gamma \vdash \mathtt{do}\ x \leftarrow v_1\ \mathtt{in}\ v_2 \colon \mathtt{M}_{\epsilon_1 \cdot \epsilon_2} B \tag{5.15}$$

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

$$\Phi' \mid \Gamma \vdash \mathtt{if}_{A,}\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2 \colon A \tag{5.16}$$

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

$$\Phi' \mid \Gamma \vdash v \colon B \tag{5.17}$$

Case Effect-Lambda: By inversion$\Phi, \alpha \mid \Gamma \vdash v \colon A$
By picking $\alpha \notin \Phi'$ using α-conversion.

$$\omega \times : \Phi', \alpha \triangleright \Phi, \alpha \tag{5.18}$$

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

$$\Phi' \mid \Gamma \vdash \Lambda \alpha . v \colon \forall a . A \tag{5.19}$$

Case Effect-Apply: By inversion, $\Phi \mid \Gamma \vdash v \colon \forall \alpha . A$, and $\Phi \vdash \epsilon$.
So by induction, $\Phi' \mid \Gamma \vdash v \colon \forall \alpha . A$
And by the well-formed-ness-theorem $\Phi' \vdash \epsilon$
Hence,

$$\Phi' \mid \Gamma \vdash v\ \epsilon \colon A\,[\epsilon / \alpha] \tag{5.20}$$

5.2 Type Environment Weakening

5.2.1 Relation

We define the ternary weakening relation $\Phi \vdash w : \Gamma' \triangleright \Gamma$ using the following rules.

- (Id)$\frac{\Phi \vdash \Gamma \mathtt{Ok}}{\Phi \vdash \iota : \Gamma \triangleright \Gamma}$
- (Project)$\frac{\Phi \vdash \omega : \Gamma' \triangleright \Gamma \quad x \notin \mathtt{dom}(\Gamma')}{\Phi \vdash \omega\pi : \Gamma, x : A \triangleright \Gamma}$
- (Extend)$\frac{\Phi \vdash \omega : \Gamma' \triangleright \Gamma \quad x \notin \mathtt{dom}(\Gamma') \quad A \leq: B}{\Phi \vdash w \times : \Gamma', x : A \triangleright \Gamma, x : B}$

5.2.2 Domain Lemma

If $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$, then $\mathtt{dom}(\Gamma) \subseteq \mathtt{dom}(\Gamma')$.

Proof:

Case Id: Then $\Gamma' = \Gamma$ and so $\mathtt{dom}(\Gamma') = \mathtt{dom}(\Gamma)$.

Case Project: By inversion and induction, $\mathtt{dom}(\Gamma) \subseteq \mathtt{dom}(\Gamma') \subseteq \mathtt{dom}(\Gamma' \cup \{x\})$

Case Extend: By inversion and induction, $\mathtt{dom}(\Gamma) \subseteq \mathtt{dom}(\Gamma')$ so

$$\mathtt{dom}(\Gamma, x : A) = \mathtt{dom}(\Gamma) \cup \{x\} \subseteq \mathtt{dom}(\Gamma') \cup \{x\} = \mathtt{dom}(\Gamma', x : A)$$

5.2.3 Theorem 1

If $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$ and $\Phi \vdash \Gamma\mathtt{Ok}$ then $\Phi \vdash \Gamma'\mathtt{Ok}$

Proof:

Case Id:

$$(\text{Id})\frac{\Phi \vdash \Gamma\mathtt{Ok}}{\Phi \vdash \iota : \Gamma \triangleright \Gamma}$$

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

Case Project:

$$(\text{Project})\frac{\Phi \vdash \omega : \Gamma' \triangleright \Gamma \quad x \notin \mathtt{dom}(\Gamma')}{\Phi \vdash \omega\pi : \Gamma, x : A \triangleright \Gamma}$$

By inversion, $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$ and $x \notin \mathtt{dom}(\Gamma')$.
Hence by induction $\Phi \vdash \Gamma'\mathtt{Ok}$, $\Phi \vdash \Gamma\mathtt{Ok}$. Since $x \notin \mathtt{dom}(\Gamma')$, we have $\Phi \vdash \Gamma', x : A\mathtt{Ok}$.

Case Extend: $(\text{Extend})\frac{\Phi \vdash \omega : \Gamma' \triangleright \Gamma \quad x \notin \mathtt{dom}(\Gamma') \quad A \leq: B}{\Phi \vdash w \times : \Gamma', x : A \triangleright \Gamma, x : B}$,
By inversion, we have
$\Phi \vdash \omega : \Gamma' \triangleright \Gamma$, $x \notin \mathtt{dom}(\Gamma')$.
Hence we have $\Phi \vdash \Gamma\mathtt{Ok}$, $\Phi \vdash \Gamma'\mathtt{Ok}$, and by the domain Lemma, $\mathtt{dom}(\Gamma) \subseteq \mathtt{dom}(\Gamma')$, hence $x \notin \mathtt{dom}(\Gamma)$. Hence, we have $\Phi \vdash \Gamma, x : A\mathtt{Ok}$ and $\Phi \vdash \Gamma', x : A\mathtt{Ok}$

5.2.4 Theorem 2

If $\Phi \mid \Gamma \vdash t \colon \tau$ and $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$ then there is a derivation of $\Phi \mid \Gamma' \vdash t \colon \tau$

Proof: We induct over the structure of typing derivations of $\Phi \mid \Gamma \vdash t \colon \tau$, assuming $\Phi \vdash \omega : \Gamma' \triangleright \Gamma$ holds.

Case Var and 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

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

$$(\text{Weaken})\frac{()\frac{\Delta_1}{\Phi \mid \Gamma'' \vdash x : A}}{\Phi \mid \Gamma'', x' : A' \vdash x \colon A} \tag{5.21}$$

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

$$\Gamma' = \Gamma''', x' : B \tag{5.22}$$
$$\Gamma = \Gamma'', x' : A' \tag{5.23}$$
$$B \leq: A \tag{5.24}$$

Case: $x = x'$ Then $A = A'$.
Then we derive the new derivation, Δ' as so:

$$\text{(Sub-type)}\frac{\text{(var)}\frac{}{\Phi|\Gamma''',x:B\vdash x:B} \quad B \leq: A}{\Phi \mid \Gamma' \vdash x\colon A} \tag{5.25}$$

Case: $x \neq x'$ Then

$$\Delta = \text{(Weaken)}\frac{()\frac{\Delta_1}{\Phi|\Gamma''\vdash x:A}}{\Phi \mid \Gamma \vdash x\colon A} \tag{5.26}$$

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

$$\Delta' = \text{(Weaken)}\frac{()\frac{\Delta_1'}{\Phi|\Gamma'''\vdash x:A}}{\Phi \mid \Gamma' \vdash x\colon A} \tag{5.27}$$

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

$$\text{(Const)}\frac{\Gamma\mathtt{Ok}}{\Gamma \vdash \mathtt{C}^A\colon A} \tag{5.28}$$

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

$$\text{(Const)}\frac{\Phi \vdash \Gamma'\mathtt{Ok}}{\Phi \mid \Gamma' \vdash \mathtt{C}^A\colon A} \tag{5.29}$$

Holds.

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

$$\Delta = \text{(Fn)}\frac{()\frac{\Delta_1}{\Phi|\Gamma,x:A\vdash v:B}}{\Phi \mid \Gamma \vdash \lambda x : A.v\colon A \to B} \tag{5.30}$$

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

$$\Phi \vdash \omega\times : (\Gamma, x : A) \triangleright (\Gamma, x : A) \tag{5.31}$$

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

$$\Delta' = \text{(Fn)}\frac{()\frac{\Delta_1'}{\Phi|\Gamma',x:A\vdash v:B}}{\Phi \mid \Gamma', x : A \vdash \lambda x : A.v\colon A \to B} \tag{5.32}$$

Case Sub-typing:

$$\text{(Sub-type)}\frac{\Phi \mid \Gamma \vdash v\colon A \quad A \leq: B}{\Phi \mid \Gamma \vdash v\colon B} \tag{5.33}$$

by inversion, we have a derivation Δ_1

$$()\frac{\Delta_1}{\Phi \mid \Gamma \vdash v\colon A} \tag{5.34}$$

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

$$\text{(Sub-type)}\frac{()\frac{\Delta_1'}{\Phi|\Gamma'\vdash v:a} \quad A \leq: B}{\Phi \mid \Gamma' \vdash v\colon B} \tag{5.35}$$

Case Return: We have the sub-derivation Δ_1 such that

$$\Delta = (\text{Return})\frac{()\frac{\Delta_1}{\Phi|\Gamma\vdash v:A}}{\Phi \mid \Gamma \vdash \texttt{return}v\colon \texttt{M}_{\texttt{1}}A} \tag{5.36}$$

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

$$\Delta' = (\text{Return})\frac{()\frac{\Delta_1'}{\Phi|\Gamma'\vdash v:A}}{\Phi \mid \Gamma' \vdash \texttt{return}v\colon \texttt{M}_{\texttt{1}}A} \tag{5.37}$$

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

$$\Delta = (\text{Apply})\frac{()\frac{\Delta_1}{\Phi|\Gamma\vdash v_1:A\to B} \quad ()\frac{\Delta_2}{\Phi|\Gamma\vdash v_2:A}}{\Phi \mid \Gamma \vdash v_1\ v_2\colon B} \tag{5.38}$$

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

$$\Delta' = (\text{Apply})\frac{()\frac{\Delta_1'}{\Phi|\Gamma'\vdash v_1:A\to B} \quad ()\frac{\Delta_2'}{\Phi|\Gamma'\vdash v_2:A}}{\Phi \mid \Gamma' \vdash v_1\ v_2\colon B} \tag{5.39}$$

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

$$\Delta = (\text{If})\frac{()\frac{\Delta_1}{\Phi|\Gamma\vdash v:\texttt{Bool}} \quad ()\frac{\Delta_2}{\Phi|\Gamma\vdash v_1:A} \quad ()\frac{\Delta_3}{\Phi|\Gamma\vdash v_2:A}}{\Phi \mid \Gamma \vdash \texttt{if}_{A,}\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2\colon A} \tag{5.40}$$

By induction, this gives us the sub-derivations $\Delta_1', \Delta_2', \Delta_3'$ such that

$$\Delta' = (\text{If})\frac{()\frac{\Delta_1'}{\Phi|\Gamma'\vdash v:\texttt{Bool}} \quad ()\frac{\Delta_2'}{\Phi|\Gamma'\vdash v_1:A} \quad ()\frac{\Delta_3'}{\Phi|\Gamma'\vdash v_2:A}}{\Phi \mid \Gamma' \vdash \texttt{if}_{A,}\ v\ \texttt{then}\ v_1\ \texttt{else}\ v_2\colon A} \tag{5.41}$$

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

$$\Delta = (\text{Bind})\frac{()\frac{\Delta_1}{\Phi|\Gamma\vdash v_1:\texttt{M}_{\mathbb{E}_1}A} \quad ()\frac{\Delta_2}{\Phi|\Gamma,x:A\vdash v_2:\texttt{M}_{\epsilon_2}B}}{\Phi \mid \Gamma \vdash \texttt{do}\ x \leftarrow v_1\ \texttt{in}\ v_2\colon \texttt{M}_{\epsilon_1\cdot\epsilon_2}B} \tag{5.42}$$

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

$$\Delta' = (\text{Bind})\frac{()\frac{\Delta_1'}{\Phi|\Gamma'\vdash v_1:\texttt{M}_{\mathbb{E}_1}A} \quad ()\frac{\Delta_2'}{\Phi|\Gamma',x:A\vdash v_2:\texttt{M}_{\epsilon_2}B}}{\Phi \mid \Gamma' \vdash \texttt{do}\ x \leftarrow v_1\ \texttt{in}\ v_2\colon \texttt{M}_{\epsilon_1\cdot\epsilon_2}B} \tag{5.43}$$

Case Effect-Abstraction: By inversion,we have derivation Δ_1 deriving

$$(\text{Effect-Abs})\frac{()\frac{\Delta_1}{\Phi,\alpha|\Gamma\vdash v:A}}{\Phi \mid \Gamma \vdash \Lambda\alpha.v\colon \forall\alpha.A} \tag{5.44}$$

By α-conversion, we have $\iota\pi : \Phi, \alpha \triangleright \Phi$, So we have $\Phi, \alpha \vdash \omega : \Gamma' \triangleright \Gamma$ so by induction, there exists Δ_1 deriving:

$$\Delta' = (\text{Effect-Abs})\frac{()\frac{\Delta_1}{\Phi,\alpha|\Gamma'\vdash v:A}}{\Phi \mid \Gamma' \vdash \Lambda\alpha.v\colon \forall\alpha.A} \tag{5.45}$$

Case Effect-Application: By inversionwe have derivation Δ_1 deriving

$$(\text{Effect-App})\frac{()\frac{\Delta_1}{\Phi|\Gamma\vdash v:\forall\alpha.A} \quad \Phi\vdash\epsilon}{\Phi \mid \Gamma \vdash v\ \epsilon\colon A\,[\epsilon/\alpha]} \tag{5.46}$$

So by induction, we have Δ_1' deriving

$$(\text{Effect-App})\frac{()\frac{\Delta_1'}{\Phi|\Gamma'\vdash v:\forall\alpha.A} \quad \Phi\vdash\epsilon}{\Phi \mid \Gamma' \vdash v\ \epsilon\colon A\,[\epsilon/\alpha]} \tag{5.47}$$

Chapter 6

Substitution

We need to define substitutions of effects on effects, effects on types, effects on terms, terms on terms.

6.1 Effect Substitutions

Define a substitution, σ as

$$\sigma ::= \diamond \mid \sigma, \alpha := \epsilon \tag{6.1}$$

Define the free-effect Variables of σ:

$$\begin{aligned} fev(\diamond) &= \emptyset \\ fev(\sigma, \alpha := \epsilon) &= fev(\sigma) \cup fev(\epsilon) \end{aligned}$$

We define the property:

$$\alpha \# \sigma \Leftrightarrow \alpha \notin (\texttt{dom}(\sigma) \cup fev(\sigma)) \tag{6.2}$$

6.1.1 Action of Effect Substitution on Effects

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

$$\sigma(\epsilon) \tag{6.3}$$

$$\sigma(e) = e \tag{6.4}$$

$$\sigma(\epsilon_1 \cdot \epsilon_2) = (\sigma(\epsilon_1)) \cdot (\sigma(\epsilon_2)) \tag{6.5}$$

$$\diamond(\alpha) = \alpha \tag{6.6}$$

$$(\sigma, \beta := \epsilon)(\alpha) = \sigma(\alpha) \tag{6.7}$$

$$(\sigma, \alpha := \epsilon)(\alpha) = \epsilon \tag{6.8}$$

6.1.2 Action of Effect Substitution on Types

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

$$\tau\,[\sigma]$$

Defined as so

$$\gamma\,[\sigma] = \gamma \tag{6.9}$$

$$(A \to \mathtt{M}_{\epsilon} B)\,[\sigma] = (A\,[\sigma]) \to \mathtt{M}_{\sigma(\epsilon)}(B\,[\sigma]) \tag{6.10}$$

$$(\mathtt{M}_{\epsilon} A)\,[\sigma] = \mathtt{M}_{\sigma(\epsilon)}(A\,[\sigma]) \tag{6.11}$$

$$(\forall \alpha . A)\,[\sigma] = \forall \alpha . (A\,[\sigma]) \quad \text{If } \alpha \# \sigma \tag{6.12}$$

6.1.3 Action of Effect-Substitution on Type Environments

Define the action of effect substitution on type environments:

$$\Gamma\,[\sigma]$$

Defined as so:

$$\diamond\,[\sigma] = \diamond$$
$$(\Gamma, x : A)\,[\sigma] = (\Gamma\,[\sigma]\,, x : (A\,[\sigma]))$$

6.1.4 Action of Effect Substitution on Terms

Define the effect of effect-substitution on terms:

$$x\,[\sigma] = x \tag{6.13}$$

$$\mathtt{C}^{A}\,[\sigma] = \mathtt{C}^{(A[\sigma])} \tag{6.14}$$

$$(\lambda x : A . C)\,[\sigma] = \lambda x : (A\,[\sigma]).(C\,[\sigma]) \tag{6.15}$$

$$(\mathtt{if}_{\epsilon, A}\ v\ \mathtt{then}\ C_1\ \mathtt{else}\ C_2)\,[\sigma] = \mathtt{if}_{\sigma(\epsilon),(A[\sigma])}\ v\,[\sigma]\ \mathtt{then}\ C_1\,[\sigma]\ \mathtt{else}\ C_2\,[\sigma] \tag{6.16}$$

$$(v_1\ v_2)\,[\sigma] = (v_1\,[\sigma])\ v_2\,[\sigma] \tag{6.17}$$

$$(\mathtt{do}\ x \leftarrow C_1\ \mathtt{in}\ C_2) = \mathtt{do}\ x \leftarrow (C_1\,[\sigma])\ \mathtt{in}\ (C_2\,[\sigma]) \tag{6.18}$$

$$(\Lambda \alpha . v)\,[\sigma] = \Lambda \alpha . (v\,[\sigma]) \quad \text{If } \alpha \# \sigma \tag{6.19}$$

$$(v\ \epsilon)\,[\sigma] = (v\,[\sigma])\ \sigma(\epsilon) \tag{6.20}$$

$$\tag{6.21}$$

6.1.5 Well-Formed-ness

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

$$\Phi' \vdash \sigma \colon \Phi \tag{6.22}$$

- (Nil) $\frac{\Phi' \mathtt{Ok}}{\Phi' \vdash \diamond : \diamond}$
- (Extend) $\frac{\Phi' \vdash \sigma : \Phi \quad \Phi' \vdash \epsilon \quad \alpha \notin \Phi}{\Phi' \vdash \sigma, \alpha := \epsilon : (\Phi, \alpha)}$

6.1.6 Property 1

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

6.1.7 Property 2

If $\Phi' \vdash \sigma \colon \Phi$ then $\omega : \Phi' \triangleright \Phi' \implies \Phi'' \vdash \sigma \colon \Phi$ since $\Phi' \vdash \epsilon \implies \Phi'' \vdash \epsilon$ and $\Phi' \mathtt{Ok} \implies \Phi'' \mathtt{Ok}$

6.1.8 Property 3

If $\Phi' \vdash \sigma\colon \Phi$ then

$$\alpha \notin \wedge \alpha \notin \Phi' \implies (\Phi', \alpha) \vdash (\sigma, \alpha := \alpha)\colon (\Phi, \alpha) \tag{6.23}$$

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

6.2 Substitution Preserves the Well-formed-ness of Effects

I.e.

$$\Phi \vdash \epsilon \wedge \Phi' \vdash \iota\colon \Phi \implies \Phi' \vdash \sigma(\epsilon) \tag{6.24}$$

Proof:

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

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

Case Var: By inversion, $\Phi = \Phi'', \alpha$ and $\Phi'', \alpha\mathtt{Ok}$. Hence byu case splitting on ι, we see that $\sigma = \sigma', \alpha := \epsilon$.

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

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

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

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

6.2.1 Substitution preserves well-formed-ness of Types

$$\Phi' \vdash \sigma\colon \Phi \wedge \Phi \vdash A \implies \Phi' \vdash A\,[\sigma] \tag{6.25}$$

Proof:

Case Ground: $\Phi'\mathtt{Ok}$ so $\Phi' \vdash \gamma$ and $\gamma\,[\sigma] = \gamma$.

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

Case Lambda: By inversion$\Phi \vdash A$ and $\Phi \vdash B$.

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

So

$$\Phi' \vdash (A\,[\sigma]) \to (B\,[\sigma]) \tag{6.26}$$

So

$$\Phi' \vdash (A \to B)\,[\sigma] \tag{6.27}$$

Case Computation: By inversion, $\Phi \vdash \epsilon$ and $\Phi \vdash A$ so by induction and substitution of effect preserving effect-well-formed-ness,

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

Case For All: By inversion, $\Phi, \alpha \vdash A$. So by picking $\alpha \notin \Phi \wedge \alpha \notin \Phi'$ using α-equivalence, we have $(\Phi', \alpha) \vdash (\sigma\alpha := \alpha) \colon (\Phi, \alpha)$.

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

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

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

6.3 Term-Term Substitutions

6.3.1 Substitutions as SNOC lists

$$\sigma ::= \diamond \mid \sigma, x := v \tag{6.28}$$

6.3.2 Trivial Properties of substitutions

$\texttt{fv}(\sigma)$

$$\texttt{fv}(\diamond) = \emptyset \tag{6.29}$$
$$\texttt{fv}(\sigma, x := v) = \texttt{fv}(\sigma) \cup \texttt{fv}(v) \tag{6.30}$$

$\texttt{dom}(\sigma)$

$$\texttt{dom}(\diamond) = \emptyset \tag{6.31}$$
$$\texttt{dom}(\sigma, x := v) = \texttt{dom}(\sigma) \cup \{x\} \tag{6.32}$$

$x\#\sigma$

$$x\#\sigma \Leftrightarrow x \notin (\texttt{fv}(\sigma) \cup \texttt{dom}(\sigma`)) \tag{6.33}$$

6.3.3 Action of substitutions

We define the effect of applying a substitution σ as

$$t\,[\sigma]$$

$$x\,[\diamond] = x \tag{6.34}$$
$$x\,[\sigma, x := v] = v \tag{6.35}$$
$$x\,[\sigma, x' := v'] = x\,[\sigma] \quad \text{If } x \neq x' \tag{6.36}$$
$$\texttt{C}^A\,[\sigma] = \texttt{C}^A \tag{6.37}$$
$$(\lambda x : A.C)\,[\sigma] = \lambda x : A.(C\,[\sigma]) \quad \text{If } x\#\sigma \tag{6.38}$$
$$(\texttt{if}_{\epsilon,A}\ v\ \texttt{then}\ C_1\ \texttt{else}\ C_2)\,[\sigma] = \texttt{if}_{\epsilon,A}\ v\,[\sigma]\ \texttt{then}\ C_1\,[\sigma]\ \texttt{else}\ C_2\,[\sigma] \tag{6.39}$$
$$(v_1\ v_2)\,[\sigma] = (v_1\,[\sigma])\ v_2\,[\sigma] \tag{6.40}$$
$$(\texttt{do}\ x \leftarrow C_1\ \texttt{in}\ C_2) = \texttt{do}\ x \leftarrow (C_1\,[\sigma])\ \texttt{in}\ (C_2\,[\sigma]) \quad \text{If } x\#\sigma \tag{6.41}$$
$$(\Lambda\alpha.v)\,[\sigma] = \Lambda\alpha.(v\,[\sigma]) \tag{6.42}$$
$$(v\ \epsilon)\,[\sigma] = (v\,[\sigma])\ \epsilon \tag{6.43}$$
$$\tag{6.44}$$

6.3.4 Well-Formed-ness

6.3.5 Simple Properties Of Substitution

If $\Gamma' \vdash \sigma \colon \Gamma$ then: **TODO: Number these**

Property 1: $\Gamma\mathtt{Ok}$ and $\Gamma'\mathtt{Ok}$ Since $\Gamma'\mathtt{Ok}$ holds by the Nil-axiom. $\Gamma\mathtt{Ok}$ holds by induction on the well-formed-ness relation.

Property 2: $\omega : \Gamma'' \triangleright \Gamma'$ implies $\Gamma'' \vdash \sigma\colon\Gamma$. By induction over well-formed-ness relation. For each $x := v$ in σ, $\Gamma'' \vdash v\colon A$ holds if $\Gamma' \vdash v\colon A$ holds.

Property 3: $x \notin (\mathtt{dom}(\Gamma) \cup \mathtt{dom}(\Gamma''))$ implies $(\Gamma', x : A) \vdash (\sigma, x := x)\colon (\Gamma, x : A)$ Since $\iota\pi : \Gamma', x : A \triangleright \Gamma'$, so by (Property 2) **TODO: Better referencing here**,

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

In addition, $\Gamma', x : A \vdash x\colon A$ trivially, so by the rule **Extend**, well-formed-ness holds for

$$(\Gamma', x : A) \vdash (\sigma, x := v)\colon (\Gamma, x : A) \tag{6.45}$$

6.4 Substitution Preserves Typing

6.4.1 Variables

Case Var

Case Weaken

6.4.2 Other Value Terms

Case Lambda

Case Constants

6.4.3 Computation Terms

Case Return

Case Apply

Case If

Case Bind

6.4.4 Sub-typing and Sub-effecting

Case Sub-type

Case Sub-effect

6.5 Semantics of Substitution

6.5.1 Denotation of Substitutions

6.5.2 Extension Lemma

6.5.3 Substitution Theorem

6.5.4 Proof For Value Terms

Case Var

Case Weaken

Case Constants

Case Lambda

Case Sub-type

6.5.5 Proof For Computation Terms

Case Return

Case Apply

Case If

Case Bind

Case Subeffect

6.6 The Identity Substitution

6.6.1 Properties of the Identity Substitution

Property 1

Property 2

Chapter 7

Beta Eta Equivalence (Soundness)

7.1 Beta and Eta Equivalence

7.1.1 Beta-Eta conversions

- (Lambda-Beta) $\frac{\Phi|\Gamma,x{:}A\vdash v{:}B \quad \Phi|\Gamma\vdash v{:}A}{\Phi|\Gamma\vdash(\lambda x{:}A.v)\ v{=_{\beta\eta}}v[x/v]{:}B}$

- (Lambda-Eta) $\frac{\Phi|\Gamma\vdash v{:}A\to B}{\Phi|\Gamma\vdash\lambda x{:}A.(v\ x){=_{\beta\eta}}v{:}A\to B}$

- (Left Unit) $\frac{\Phi|\Gamma\vdash v{:}A \quad \Phi|\Gamma,x{:}A\vdash v{:}\mathtt{M}_\epsilon B}{\Phi|\Gamma\vdash\mathtt{do}\ x\leftarrow\mathtt{return}v\ \mathtt{in}\ v{=_{\beta\eta}}v[V/x]{:}\mathtt{M}_\epsilon B}$

- (Right Unit) $\frac{\Phi|\Gamma\vdash v{:}\mathtt{M}_\epsilon A}{\Phi|\Gamma\vdash\mathtt{do}\ x\leftarrow v\ \mathtt{in}\ \mathtt{return}x{=_{\beta\eta}}v{:}\mathtt{M}_\epsilon A}$

- (Associativity) $\frac{\Phi|\Gamma\vdash v_1{:}\mathtt{M}_{\epsilon_1}A \quad \Phi|\Gamma,x{:}A\vdash v_2{:}\mathtt{M}_{\epsilon_2}B \quad \Phi|\Gamma,y{:}B\vdash v_3{:}\mathtt{M}_{\epsilon_3}C}{\Phi|\Gamma\vdash\mathtt{do}\ x\leftarrow v_1\ \mathtt{in}\ (\mathtt{do}\ y\leftarrow v_2\ \mathtt{in}\ v_3){=_{\beta\eta}}\mathtt{do}\ y\leftarrow(\mathtt{do}\ x\leftarrow v_1\ \mathtt{in}\ v_2)\ \mathtt{in}\ v_3{:}\mathtt{M}_{\epsilon_1\cdot\epsilon_2\cdot\epsilon_3}C}$

- (Unit) $\frac{\Phi|\Gamma\vdash v{:}\mathtt{Unit}}{\Phi|\Gamma\vdash v{=_{\beta\eta}}\mathtt{()}{:}\mathtt{Unit}}$

- (if-true) $\frac{\Phi|\Gamma\vdash v_1{:}A \quad \Phi|\Gamma\vdash v_2{:}A}{\Phi|\Gamma\vdash\mathtt{if}_{A,}\ \mathtt{true}\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2{=_{\beta\eta}}v_1{:}A}$

- (if-false) $\frac{\Phi|\Gamma\vdash v_2{:}A \quad \Phi|\Gamma\vdash v_1{:}A}{\Phi|\Gamma\vdash\mathtt{if}_{A,}\ \mathtt{false}\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2{=_{\beta\eta}}v_2{:}A}$

- (If-Eta) $\frac{\Phi|\Gamma,x{:}\mathtt{Bool}\vdash v{:}A \quad \Phi|\Gamma\vdash v{:}\mathtt{Bool}}{\Phi|\Gamma\vdash\mathtt{if}_{A,}\ v\ \mathtt{then}\ v[\mathtt{true}/x]\ \mathtt{else}\ v\left[\mathtt{false}/x\right]{=_{\beta\eta}}v[V/x]{:}A}$

- (Effect-beta) $\frac{\Phi\vdash\epsilon \quad \Phi,\alpha|\Gamma\vdash v{:}A}{\Phi|\Gamma\vdash(\Lambda\alpha.v\ \epsilon){=_{\beta\eta}}v[\epsilon/\alpha]{:}A[\epsilon/\alpha]}$

- (Effect-eta) $\frac{\Phi|\Gamma\vdash v{:}\forall\alpha.A}{\Phi|\Gamma\vdash\Lambda\alpha.(v\ \alpha){=_{\beta\eta}}v{:}\forall\alpha.A}$

7.1.2 Equivalence Relation

- (Reflexive) $\frac{\Phi|\Gamma\vdash v{:}A}{\Phi|\Gamma\vdash v{=_{\beta\eta}}v{:}A}$

- (Symmetric) $\frac{\Phi|\Gamma\vdash v_1{=_{\beta\eta}}v_2{:}A}{\Phi|\Gamma\vdash v_2{=_{\beta\eta}}v_1{:}A}$

- (Transitive) $\frac{\Phi|\Gamma\vdash v_1{=_{\beta\eta}}v_2{:}A \quad \Phi|\Gamma\vdash v_2{=_{\beta\eta}}v_3{:}A}{\Phi|\Gamma\vdash v_1{=_{\beta\eta}}v_3{:}A}$

7.1.3 Congruences

- (Effect-Abs) $\frac{\Phi,\alpha|\Gamma\vdash v_1=_{\beta\eta}v_2:A}{\Phi|\Gamma\vdash\Lambda\alpha.v_1=_{\beta\eta}\Lambda\alpha.v_2:\forall\alpha.A}$
- (Effect-Apply) $\frac{\Phi|\Gamma\vdash v_1=_{\beta\eta}v_2:\forall\alpha.A \quad \Phi\vdash\epsilon}{\Phi|\Gamma\vdash v_1\ \epsilon=_{\beta\eta}v_2\ \epsilon:A[\epsilon/\alpha]}$
- (Lambda) $\frac{\Phi|\Gamma,x:A\vdash v_1=_{\beta\eta}v_2:B}{\Phi|\Gamma\vdash\lambda x:A.v_1=_{\beta\eta}\lambda x:A.v_2:A\to B}$
- (Return) $\frac{\Phi|\Gamma\vdash v_1=_{\beta\eta}v_2:A}{\Phi|\Gamma\vdash\mathtt{return}v_1=_{\beta\eta}\mathtt{return}v_2:\mathtt{M}_{\mathtt{1}}A}$
- (Apply) $\frac{\Phi|\Gamma\vdash v_1=_{\beta\eta}v_1':A\to B \quad \Phi|\Gamma\vdash v_2=_{\beta\eta}v_2':A}{\Phi|\Gamma\vdash v_1\ v_2=_{\beta\eta}v_1'\ v_2':B}$
- (Bind) $\frac{\Phi|\Gamma\vdash v_1=_{\beta\eta}v_1':\mathtt{M}_{\epsilon_1}A \quad \Phi|\Gamma,x:A\vdash v_2=_{\beta\eta}v_2':\mathtt{M}_{\epsilon_2}B}{\Phi|\Gamma\vdash\mathtt{do}\ x\leftarrow v_1\ \mathtt{in}\ v_2=_{\beta\eta}\mathtt{do}\ c\leftarrow v_1'\ \mathtt{in}\ v_2':\mathtt{M}_{\epsilon_1\cdot\epsilon_2}B}$
- (If) $\frac{\Phi|\Gamma\vdash v=_{\beta\eta}v':\mathtt{Bool} \quad \Phi|\Gamma\vdash v_1=_{\beta\eta}v_1':A \quad \Phi|\Gamma\vdash v_2=_{\beta\eta}v_2':A}{\Phi|\Gamma\vdash\mathtt{if}_{A,}\ v\ \mathtt{then}\ v_1\ \mathtt{else}\ v_2=_{\beta\eta}\mathtt{if}_{A,}\ v\ \mathtt{then}\ v_1'\ \mathtt{else}\ v_2':A}$
- (Subtype) $\frac{\Phi|\Gamma\vdash v=_{\beta\eta}v':A \quad A\leq:B}{\Phi|\Gamma\vdash v=_{\beta\eta}v':B}$

7.2 Beta-Eta Equivalence Implies Both Sides Have the Same Type

7.2.1 Equivalence Relations

Case Symmetric

Case Transitive

7.2.2 Beta conversions

Case Lambda

Case Associativity

Case Eta

Case If-True

7.2.3 Congruences

Case Lambda

Case Return

Case Apply

Case Bind

Case If

Case Subtype

Case subeffect

7.3 Beta-Eta equivalent terms have equal denotations

7.3.1 Equivalence Relation

Case Reflexive

Case Symmetric

Case Transitive

7.3.2 Beta Conversions

Case Lambda

Case Left Unit

Case Right Unit

Case Associative

Case Eta

Case If-True

Case If-False

7.3.3 Case If-Eta

7.3.4 Congruences

Case Lambda

Case Return

Case Apply

Case Bind

Case If

Case Subtype

Case subeffect