Polymorphic algebraic effects: theoretical properties and implementation

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Chapter 1

Introduction

Chapter 2

The language

We will study the deep handler calculus and type-and-effect system formulated in [2]. It is a refreshingly minimal language—the call-by-value lambda calculus with a few extensions to be able to express the essence of algebraic effects. There is only one unnamed universal operation, performed $\mathsf{do}\ v$. To be able to simulate calculi with named effects (and more), the *lift* operator, written $[e]$, is introduced. When operations are performed inside the expression e enclosed by lift, the nearest handler will be skipped and the operation will be handled by the next one instead. Naturally, the operator composes, so multiple enclosing lifts means multiple handlers skipped. In contrast to most work on algebraic effects, the effect-tracking system here is structural, we do not have any concept of predefined or user-defined (named) signatures of effects. Finally, the language features polymorphic expressions and polymorphic operations.

$$
\begin{aligned}
\mathrm{Val} \ni v, u &::= x \mid \lambda x.\, e \\
\mathrm{Exp} \ni e &::= v \mid e\ e \mid [e] \mid \mathsf{do}\ v \mid \mathsf{handle}\ e\, \{x, r.\, e;\ x.\, e\} \\
\mathrm{ECont} \ni K &::= \square \mid K\ e \mid v\ K \mid [K] \mid \mathsf{handle}\ K\, \{x, r.\, e;\ x.\, e\}
\end{aligned}
$$

Figure 2.1: Syntax.

$$\frac{}{0\text{-free}(\square)} \qquad \frac{n\text{-free}(K)}{n\text{-free}(K\ e)} \qquad \frac{n\text{-free}(K)}{n\text{-free}(v\ K)} \qquad \frac{n\text{-free}(K)}{n+1\text{-free}([K])}$$

$$\frac{n+1\text{-free}(K)}{n\text{-free}(\mathsf{handle}\ K\ \{x, r.\, e_h;\ x.\, e_r\})}$$

Figure 2.2: Evaluation context freeness.

$$\frac{e_1 \mapsto e_2}{K[e_1] \to K[e_2]} \qquad (\lambda x.\, e)\ v \mapsto e\{v/x\} \qquad [v] \mapsto v$$

$$\frac{0\text{-free}(K) \qquad v_c = \lambda z.\, \mathsf{handle}\ K[z]\ \{x, r.\, e_h;\ x.\, e_r\}}{\mathsf{handle}\ K[\mathsf{do}\ v]\ \{x, r.\, e_h;\ x.\, e_r\} \mapsto e_h\{v/x\}\{v_c/r\}}$$

$$\mathsf{handle}\ v\ \{x, r.\, e_h;\ x.\, e_r\} \mapsto e_r\{v/x\}$$

Figure 2.3: Single-step reduction.

$$\kappa ::= \mathsf{T} \mid \mathsf{E} \mid \mathsf{R} \qquad\qquad \sigma, \tau, \varepsilon, \rho ::= \alpha \mid \tau \to_\rho \tau \mid \forall \alpha :: \kappa.\, \tau \mid \iota \mid \Delta.\, \tau \Rightarrow \tau \mid \varepsilon \cdot \rho$$

$$\frac{x : \tau \in \Gamma}{\Delta; \Gamma \vdash x : \tau \,/\, \iota} \qquad \frac{\Delta \vdash \tau_1 :: \mathsf{T} \qquad \Delta; \Gamma, x : \tau_1 \vdash e : \tau_2 \,/\, \rho}{\Delta; \Gamma \vdash \lambda x.\, e : \tau_1 \to_\rho \tau_2 \,/\, \iota}$$

$$\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \to_\rho \tau_2 \,/\, \rho \qquad \Delta; \Gamma \vdash e_2 : \tau_1 \,/\, \rho}{\Delta; \Gamma \vdash e_1\, e_2 : \tau_2 \,/\, \rho} \qquad \frac{\Delta \vdash \varepsilon :: \mathsf{E} \qquad \Delta; \Gamma \vdash e : \tau \,/\, \rho}{\Delta; \Gamma \vdash [e] : \tau \,/\, \varepsilon \cdot \rho}$$

$$\frac{\Delta, \alpha :: \kappa; \Gamma \vdash e : \tau \,/\, \iota}{\Delta; \Gamma \vdash e : \forall \alpha :: \kappa.\, \tau \,/\, \iota} \qquad \frac{\Delta \vdash \sigma :: \kappa \qquad \Delta; \Gamma \vdash e : \forall \alpha :: \kappa.\, \tau \,/\, \rho}{\Delta; \Gamma \vdash e : \tau\{\sigma/\alpha\} \,/\, \rho}$$

$$\frac{\Delta \vdash \tau_1 <: \tau_2 \qquad \Delta \vdash \rho_1 <: \rho_2 \qquad \Delta; \Gamma \vdash e : \tau_1 \,/\, \rho_1}{\Delta; \Gamma \vdash e : \tau_2 \,/\, \rho_2}$$

$$\frac{\Delta; \Gamma \vdash v : \delta(\tau_1) \,/\, \iota \qquad \Delta \vdash \delta :: \Delta' \qquad \Delta \vdash \Delta'.\, \tau_1 \Rightarrow \tau_2 :: \mathsf{E}}{\Delta; \Gamma \vdash \mathsf{do}\; v : \delta(\tau_2) \,/\, (\Delta'.\, \tau_1 \Rightarrow \tau_2)}$$

$$\frac{\begin{array}{c}\Delta; \Gamma \vdash e : \tau \,/\, (\Delta'.\, \tau_1 \Rightarrow \tau_2) \cdot \rho \\ \Delta, \Delta'; \Gamma, x : \tau_1, r : \tau_2 \to_\rho \tau_r \vdash e_h : \tau_r \,/\, \rho \qquad \Delta; \Gamma, x : \tau \vdash e_r : \tau_r \,/\, \rho\end{array}}{\Delta; \Gamma \vdash \mathsf{handle}\; e\; \{x, r.\, e_h; x.\, e_r\} : \tau_r \,/\, \rho}$$

Figure 2.4: Type system.

$$\frac{\alpha :: \kappa \in \Delta}{\Delta \vdash \alpha :: \kappa} \qquad \frac{\Delta \vdash \tau_1 :: \mathsf{T} \qquad \Delta \vdash \rho :: \mathsf{R} \qquad \Delta \vdash \tau_2 :: \mathsf{T}}{\Delta \vdash \tau_1 \to_\rho \tau_2 :: \mathsf{T}} \qquad \frac{\Delta, \alpha :: \kappa \vdash \tau :: \mathsf{T}}{\Delta \vdash \forall \alpha :: \kappa.\, \tau :: \mathsf{T}}$$

$$\frac{}{\Delta \vdash \iota :: \mathsf{R}} \qquad \frac{\Delta \vdash \varepsilon :: \mathsf{E} \qquad \Delta \vdash \rho :: \mathsf{R}}{\Delta \vdash \varepsilon \cdot \rho :: \mathsf{R}} \qquad \frac{\Delta, \Delta' \vdash \tau_1 :: \mathsf{T} \qquad \Delta, \Delta' \vdash \tau_2 :: \mathsf{T}}{\Delta \vdash \Delta'.\, \tau_1 \Rightarrow \tau_2 :: \mathsf{E}}$$

Figure 2.5: Well-formedness of types and rows

$$\frac{}{\Delta \vdash \sigma <: \sigma} \qquad \frac{\Delta \vdash \tau_2^1 <: \tau_1^1 \qquad \Delta \vdash \rho_1 <: \rho_2 \qquad \Delta \vdash \tau_1^2 <: \tau_2^2}{\Delta \vdash \tau_1^1 \to_{\rho_1} \tau_1^2 <: \tau_2^1 \to_{\rho_2} \tau_2^2}$$

$$\frac{\Delta, \alpha :: \kappa \vdash \tau_1 <: \tau_2}{\Delta \vdash \forall \alpha :: \kappa.\, \tau_1 <: \forall \alpha :: \kappa.\, \tau_2} \qquad \frac{\Delta \vdash \rho :: \mathsf{R}}{\Delta \vdash \iota <: \rho} \qquad \frac{\Delta \vdash \rho_1 <: \rho_2}{\Delta \vdash \varepsilon \cdot \rho_1 <: \varepsilon \cdot \rho_2}$$

Figure 2.6: Subtyping.

Chapter 3

The logical relation

[todo introduction to logical relations]

The logical relation is inspired by [1]. Some changes are due to language differences: we have only one universal operation which simplifies the treatment of effects, polymorphism does not manifest at the expression level—we do not have type lambdas, and our operations can be polymorphic. Instead of a binary step-indexed relation, our goal is to build a unary relation without step-indexing.

3.1 Definition

First, we define the interpretations of kinds. We call them the spaces of *semantic types* or, in the specific cases of E and R, *semantic effects*.

$$\begin{aligned} [\![\mathsf{T}]\!] &= \mathcal{P}(\mathrm{Val}) = \mathsf{Type}, \\ [\![\mathsf{E}]\!] &= \mathcal{P}(\mathrm{Exp} \times \{0\} \times \mathsf{Type}) \\ [\![\mathsf{R}]\!] &= \mathcal{P}(\mathrm{Exp} \times \mathbb{N} \times \mathsf{Type}) \end{aligned}$$

Semantic types are simply sets of closed values. Semantic effects are sets of triples, which aim to describe a situation in which an expression being evaluated performs an effect. The components of such a triple are: the argument of the operation, the freeness of the enclosing context beyond which the operation can be handled, and the semantic type of values we can call the resumption with.

We interpret type contexts as mappings from type variables to semantic types:

$$[\![\Delta]\!] = \{\eta \mid \forall \alpha :: \kappa \in \Delta.\, \eta(\alpha) \in [\![\kappa]\!]\}.$$

We define the interpretations of types and effects as well as relations $\mathcal{E}$ on expressions and $\mathcal{S}$ on control-stuck terms by structural induction. We parameterize the definitions by a mapping η from type variables to semantic types.

The interpretations of types are mostly standard, but we additionally have to consider effect annotations, as we can see in the case of the function type.

A polymorphic type is interpreted, as usual, as the intersection of the interpretations for all possible choices of the semantic type for the type variable. Interestingly, we can see that a polymorphic effect is interpreted as the *union* of the interpretations of the effect for all possible choices of the semantic types for the type variables.

$$
\begin{aligned}
[\![\alpha]\!]_\eta &= \eta(\alpha) \\
[\![\tau_1 \to_\rho \tau_2]\!]_\eta &= \{\lambda x.\, e \mid \forall v \in [\![\tau_1]\!]_\eta.\, e\{v/x\} \in \mathcal{E}[\![\tau_2/\rho]\!]_\eta\} \\
[\![\forall \alpha :: \kappa.\, \tau]\!]_\eta &= \{v \mid \forall \mu \in [\![\kappa]\!].\, v \in [\![\tau]\!]_{[\alpha \mapsto \mu]\eta}\} \\
[\![\Delta.\, \tau_1 \Rightarrow \tau_2]\!]_\eta &= \{(v, 0, [\![\tau_2]\!]_{\eta\eta'}) \mid \eta' \in [\![\Delta]\!] \wedge v \in [\![\tau_1]\!]_{\eta\eta'}\} \\
[\![\varepsilon \cdot \rho]\!]_\eta &= [\![\varepsilon]\!]_\eta \cup \{(v, n+1, \mu) \mid (v, n, \mu) \in [\![\rho]\!]_\eta\} \\
[\![\iota]\!]_\eta &= \emptyset
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{E}[\![\tau/\rho]\!]_\eta(X) &= \{e \mid \exists v \in [\![\tau]\!]_\eta.\, e \to^* v \vee \exists e' \in \mathcal{S}[\![\tau/\rho]\!]_\eta(X).\, e \to^* e'\} \\
\mathcal{S}[\![\tau/\rho]\!]_\eta(X) &= \{K[\mathsf{do}\ v] \mid \exists n, \mu.\, (v, n, \mu) \in [\![\rho]\!]_\eta \wedge n\text{-free}(K) \wedge \forall u \in \mu.\, K[u] \in X\}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{E}[\![\tau/\rho]\!]_\eta &= \bigcap \{X \mid \mathcal{E}[\![\tau/\rho]\!]_\eta(X) \subseteq X\} \\
\mathcal{S}[\![\tau/\rho]\!]_\eta &= \mathcal{S}[\![\tau/\rho]\!]_\eta(\mathcal{E}[\![\tau/\rho]\!]_\eta)
\end{aligned}
$$

The definition of the set $\mathcal{E}[\![\tau/\rho]\!]_\eta$ is recursive and we interpret it inductively. To describe the construction in more detail, we temporarily overload notation and define operators $\mathcal{S}[\![\tau/\rho]\!]_\eta$ and $\mathcal{E}[\![\tau/\rho]\!]_\eta$ on sets of expressions (denoted by X). They are clearly monotone, so by the Knaster-Tarski theorem the fixed-point equation $\mathcal{E}[\![\tau/\rho]\!]_\eta(X) = X$ has a least solution. Additionally, it can be characterized as the intersection of all $\mathcal{E}[\![\tau/\rho]\!]_\eta$-closed sets. We immediately obtain the Tarski induction principle.

Lemma 1 (Tarski induction principle). *If $\mathcal{E}[\![\tau/\rho]\!]_\eta(X) \subseteq X$, then $\mathcal{E}[\![\tau/\rho]\!]_\eta \subseteq X$.*

By expanding out the definition of the function $\mathcal{E}[\![\tau/\rho]\!]_\eta$ and treating X as a predicate P, we get the more familiar principle of structural induction on $\mathcal{E}[\![\tau/\rho]\!]_\eta$.

Lemma 2 (Induction principle). *Assume P is a predicate on closed expressions and*

- *if e evaluates to a value in $[\![\tau]\!]_\eta$, then $P(e)$ holds; and*
- *if e reduces to some $K[\mathsf{do}\ v]$ such that there exist $(v, n, \mu) \in [\![\rho]\!]_\eta$ such that n-free(K) and $P(K[u])$ holds for all $u \in \mu$, then $P(e)$ holds.*

Then $P(e)$ holds for all $e \in \mathcal{E}[\![\tau/\rho]\!]_\eta$.

We also note some straightforward but useful properties of the relations.

Lemma 3 (Value inclusion). *For any τ and ρ we have $[\![\tau]\!]_\eta \subseteq \mathcal{E}[\![\tau/\rho]\!]_\eta$.*

Lemma 4 (Control-stuck inclusion). *For any τ and ρ we have $\mathcal{S}[\![\tau/\rho]\!]_\eta \subseteq \mathcal{E}[\![\tau/\rho]\!]_\eta$.*

Lemma 5 (Closedness under antireduction). *If $e \to^* e' \in \mathcal{E}[\![\tau/\rho]\!]_\eta$, then $e \in \mathcal{E}[\![\tau/\rho]\!]_\eta$.*

Lemma 6. *If $[\![\tau_1]\!]_\eta \subseteq [\![\tau_2]\!]_\eta$ and $[\![\rho_1]\!]_\eta \subseteq [\![\rho_2]\!]_\eta$, then $\mathcal{S}[\![\tau_1/\rho_1]\!]_\eta \subseteq \mathcal{S}[\![\tau_2/\rho_2]\!]_\eta$ and $\mathcal{E}[\![\tau_1/\rho_1]\!]_\eta \subseteq \mathcal{E}[\![\tau_2/\rho_2]\!]_\eta$.*

3.2 Compatibility lemmas

We want to establish that $\vdash e : \tau \,/\, \iota$ implies $e \in \mathcal{E}[\![\tau/\iota]\!]$.

For this purpose we will prove a semantic counterpart of each typing rule. First, we need to define a counterpart to the typing judgment. Unlike typing judgments, our relations are on closed terms only, so we get around that by using substitution. We define semantic entailment as

$$\Delta; \Gamma \models e : \tau \,/\, \rho \iff \forall \eta \in [\![\Delta]\!]. \forall \gamma \in [\![\Gamma]\!]_\eta. \gamma(e) \in \mathcal{E}[\![\tau/\rho]\!]_\eta,$$

where $[\![\Gamma]\!]_\eta = \{\gamma \mid \forall x : \tau \in \Gamma. \gamma(x) \in [\![\tau]\!]_\eta\}$ contains expression-level variable substitutions.

Lemma 7 (Variable compatibility)**.**

Proof. Assume $x : \tau \in \Gamma$. We want to prove $\Delta; \Gamma \models x : \tau \,/\, \iota$. Take any $\eta \in [\![\Delta]\!]$ and $\gamma \in [\![\Gamma]\!]_\eta$. We want to show $\gamma(x) \in \mathcal{E}[\![\tau/\iota]\!]_\eta$. From the definition of $[\![\Gamma]\!]_\eta$ we know that $\gamma(x) \in [\![\tau]\!]_\eta$, so by lemma 3 we have $\gamma(x) \in \mathcal{E}[\![\tau/\iota]\!]_\eta$. $\square$

Lemma 8 (Abstraction compatibility)**.**

Proof. Assume $\Delta \vdash \tau_1 :: \mathsf{T}$ and $\Delta; \Gamma, x : \tau_1 \models e : \tau_2 \,/\, \rho$. We want to prove $\Delta; \Gamma \models \lambda x.\, e : \tau_1 \to_\rho \tau_2 \,/\, \iota$. Take any $\eta \in [\![\Delta]\!]$ and $\gamma \in [\![\Gamma]\!]_\eta$. By lemma 3 it suffices to show $\gamma(\lambda x.\, e) = \lambda x.\, \gamma(e) \in [\![\tau_1 \to_\rho \tau_2]\!]_\eta$. So take any $v \in [\![\tau_1]\!]_\eta$. We need to show $\gamma(e)\{v/x\} \in \mathcal{E}[\![\tau_2/\rho]\!]_\eta$. Let $\gamma' = \gamma'[x \mapsto v]$. Then $\gamma' \in [\![\Gamma, x : \tau_1]\!]_\eta$, so $\gamma(e)\{v/x\} = \gamma'(e) \in \mathcal{E}[\![\tau_2/\rho]\!]_\eta$. $\square$

For clarity of presentation, in the following we will assume Γ empty, i.e. an interpretation of Γ was already substituted.

Lemma 9 (Lift compatibility)**.**

Proof. Assume $\Delta \vdash \tau :: \mathsf{T}$, $\Delta \vdash \varepsilon :: \mathsf{E}$, and $\Delta \vdash \rho :: \mathsf{R}$. Take any $\eta \in [\![\Delta]\!]$. We will show by induction on $e \in \mathcal{E}[\![\tau/\rho]\!]_\eta$ that $[e] \in \mathcal{E}[\![\tau/\varepsilon \cdot \rho]\!]_\eta$.

If $e \to^* K[\mathsf{do}\ v]$ and there exists $(v, n, \mu) \in [\![\rho]\!]_\eta$ such that n-free(K) and for all $u \in \mu$ the induction hypothesis holds for $K[u]$, then we have $(v, n+1, \mu) \in [\![\varepsilon \cdot \rho]\!]_\eta$, $n+1$-free$([K])$, and $\forall u \in \mu. [K[u]] \in \mathcal{E}[\![\tau/\varepsilon \cdot \rho]\!]_\eta$. So $[K[\mathsf{do}\ v]] \in \mathcal{S}[\![\tau/\varepsilon \cdot \rho]\!]_\eta$ and $[e] \in \mathcal{E}[\![\tau/\varepsilon \cdot \rho]\!]_\eta$ by antireduction.

If $e \to^* v \in [\![\tau]\!]_\eta$, then $[e] \to^* [v] \to v$, so $[e] \in \mathcal{E}[\![\tau/\varepsilon \cdot \rho]\!]_\eta$. $\square$

Lemma 10 (Application compatibility)**.**

Proof. Fix any well-formed Δ and $\tau_1 \to_\rho \tau_2$. Take any $\eta \in [\![\Delta]\!]$ and $e_2 \in \mathcal{E}[\![\tau_1/\rho]\!]_\eta$. We will show by induction on $e_1 \in \mathcal{E}[\![\tau_1 \to_\rho \tau_2/\rho]\!]_\eta$ that $e_1\ e_2 \in \mathcal{E}[\![\tau_2/\rho]\!]_\eta$.

If $e_1 \to^* K_1[\mathsf{do}\ v]$ and there exists $(v, n, \mu) \in [\![\rho]\!]_\eta$ such that n-free(K_1) and for all $u \in \mu$ the inductive hypothesis holds for $K_1[u]$, then $K_1[\mathsf{do}\ v]\ e_2 \in \mathcal{S}[\![\tau_2/\rho]\!]_\eta$, since n-free$(K_1\ e_2)$. By antireduction $e_1\ e_2 \in \mathcal{E}[\![\tau_2/\rho]\!]_\eta$.

Now assume $e_1 \to^* (\lambda x.\, e) \in [\![\tau_1 \to_\rho \tau_2/\rho]\!]_\eta$. We will show by induction on $e_2 \in \mathcal{E}[\![\tau_1/\rho]\!]_\eta$ that $(\lambda x.\, e)\ e_2 \in \mathcal{E}[\![t_2/\rho]\!]_\eta$ and the claim will follow by antireduction.

If $e_2 \to^* K_2[\mathsf{do}\ v]$ and there exists $(v, n, \mu) \in [\![\rho]\!]_\eta$ such that n-free(K_2) and for all $u \in \mu$ the inductive hypothesis holds for $K_2[u]$, then $(\lambda x.\, e)\ K_2[\mathsf{do}\ v] \in \mathcal{S}[\![\tau_2/\rho]\!]_\eta$, since n-free$((\lambda x.\, e)\ K_2)$. By antireduction $(\lambda x.\, e)\ e_2 \in \mathcal{E}[\![\tau_2/\rho]\!]_\eta$.

If $e_2 \to^* v \in [\![\tau_1]\!]_\eta$, then $(\lambda x.\, e)\ e_2 \to^* (\lambda x.\, e)\ v \to e\{v/x\} \in \mathcal{E}[\![\tau_2/\rho]\!]_\eta$. $\square$

Lemma 11 (Handle compatibility).

Proof. Assume $\Delta, \Delta'; x : \tau_1, r : \tau_2 \to_\rho \tau_r \models e_h : \tau_r \,/\, \rho$ and $\Delta; x : \tau \models e_r : \tau_r \,/\, \rho$. Let h stand for $\{x, r.\, e_h;\, x.\, e_r\}$. Take any $\eta \in [\![\Delta]\!]$. We will show by induction on $e \in \mathcal{E}[\![\tau/(\Delta'.\, \tau_1 \Rightarrow \tau_2) \cdot \rho]\!]_\eta$ that $\mathsf{handle}\; e\, h \in \mathcal{E}[\![\tau_r/\rho]\!]_\eta$. Note that only τ_1 and τ_2 require Δ' to be in context.

If $e \to^* v \in [\![\tau]\!]_\eta$, then $\mathsf{handle}\; e\, h \to^* e_r\{v/x\} \in \mathcal{E}[\![\tau_r/\rho]\!]_\eta$, so the claim follows by antireduction.

Now assume $e \to^* K[\mathsf{do}\; v]$ and we have $(v, n, \mu) \in [\![(\Delta'.\, \tau_1 \Rightarrow \tau_2) \cdot \rho]\!]_\eta$ such that n-free(K) and for all $u \in \mu$ the induction hypothesis holds for $K[u]$.

If $n = 0$, then $(v, n, \mu) \in [\![\tau_1 \Rightarrow \tau_2]\!]_{\eta\eta'}$ for some $\eta' \in [\![\Delta']\!]$. More specifically, $v \in [\![\tau_1]\!]_{\eta\eta'}$ and $\mu = [\![\tau_2]\!]_{\eta\eta'}$. We have $\mathsf{handle}\; e\, h \to^* \mathsf{handle}\; K[\mathsf{do}\; v]\, h \to e_h\{v/x\}\{v_c/r\}$, where $v_c = \lambda z.\, \mathsf{handle}\; K[z]\, h$. To show $v_c \in [\![\tau_2 \to_\rho \tau_r]\!]_{\eta\eta'}$, take any $u \in [\![\tau_2]\!]_{\eta\eta'}$ and show $\mathsf{handle}\; K[u]\, h \in \mathcal{E}[\![\tau_r/\rho]\!]_{\eta\eta'} = \mathcal{E}[\![\tau_r/\rho]\!]_\eta$. Which holds by induction hypothesis. Therefore, $e_h\{v/x\}\{v_c/r\}$ is in $\mathcal{E}[\![\tau_r/\rho]\!]_\eta$ and so is $\mathsf{handle}\; e\; h$.

If $n > 0$, then $\mathsf{handle}\; K[\mathsf{do}\; v]\, h \in \mathcal{S}[\![\tau_r/\rho]\!]_\eta$, since $n-1$-free$(\mathsf{handle}\; K\, h)$, $(v, n-1, \mu) \in [\![\rho]\!]_\eta$, and $\forall u \in \mu.\, \mathsf{handle}\; K[u]\, h \in \mathcal{E}[\![\tau_r/\rho]\!]_\eta$. Again, the claim follows by antireduction.

□

Lemma 12. *If Δ and Δ' disjoint, $\Delta \vdash \delta :: \Delta'$, and $\Delta, \Delta' \vdash \tau :: \kappa$, $\eta \in [\![\Delta]\!]$, and η' extends η by mappings $\alpha \mapsto [\![\delta(\alpha)]\!]_\eta$, then $[\![\tau]\!]_{\eta'} = [\![\delta(\tau)]\!]_\eta$.*

Proof. By induction on the kinding rules.

If $\tau = \alpha \in \Delta$, then both sides are equal to $\eta(\alpha)$.

If $\tau = \alpha \in \Delta'$, then equality follows from the definition of η'.

If $\tau = \iota$, then both sides are empty.

If $\tau = \forall \alpha :: \kappa.\, \tau'$, then $[\![\tau]\!]_{\eta'} = \bigcap\{[\![\tau']\!]_{\eta'[\alpha\mapsto\mu]} \mid \mu \in [\![\kappa]\!]\}$ and $[\![\delta(\tau)]\!]_\eta = \bigcap\{[\![\delta(\tau')]\!]_{\eta[\alpha\mapsto\mu]} \mid \mu \in [\![\kappa]\!]\}$, which are equal by the inductive hypothesis (taking $\Delta, \alpha :: \kappa$ as Δ in the statement).

If $\tau = \Delta''.\, \tau_1 \Rightarrow \tau_2$, then $[\![\tau]\!]_{\eta'} = \{(v, 0, [\![\tau_2]\!]_{\eta'\eta''}) \mid \eta'' \in [\![\Delta'']\!] \wedge v \in [\![\tau_1]\!]_{\eta'\eta''}\}$ and $[\![\delta(\tau)]\!]_\eta = \{(v, 0, [\![\delta(\tau_2)]\!]_{\eta\eta''}) \mid \eta'' \in [\![\Delta'']\!] \wedge v \in [\![\delta(\tau_1)]\!]_{\eta\eta''}\}$, which are equal q‘by induction (taking Δ, Δ'' as Δ in the statement).

If $\tau = \varepsilon \cdot \rho$, then $[\![\tau]\!]_{\eta'} = [\![\varepsilon]\!]_{\eta'} \cup \{(v, n+1, \mu) \mid (v, n, \mu) \in [\![\rho]\!]_{\eta'}\}$ and $[\![\delta(\tau)]\!]_\eta = [\![\delta(\varepsilon)]\!]_\eta \cup \{(v, n+1, \mu) \mid (v, n, \mu) \in [\![\delta(\rho)]\!]_\eta\}$, which are equal by the inductive hypothesis. □

Lemma 13 (Do compatibility).

Proof. Assume $\Delta \vdash \delta :: \Delta'$, $\Delta \vdash \Delta'.\, \tau_1 \to \tau_2 :: \mathsf{E}$. Take any $\eta \in [\![\Delta]\!]$. Assume $v \in [\![\delta(\tau_1)]\!]_\eta$. We want to show $\mathsf{do}\; v \in \mathcal{E}[\![\delta(\tau_2)/(\Delta'.\, \tau_1 \Rightarrow \tau_2)]\!]_\eta$.

By lemma 4 it suffices to show $\mathsf{do}\; v \in \mathcal{S}[\![\delta(\tau_2)/(\Delta'.\, \tau_1 \Rightarrow \tau_2)]\!]_\eta$. By taking the empty context in the definition of $\mathcal{S}$ and lemma 3, it suffices to show $(v, 0, [\![\delta(\tau_2)]\!]_\eta) \in [\![\Delta'.\, \tau_1 \Rightarrow \tau_2]\!]_\eta$. From the interpretation of polymorphic effects, it would be enough to show $(v, 0, [\![\delta(\tau_2)]\!]_\eta) \in [\![\tau_1 \Rightarrow \tau_2]\!]_{\eta'}$, where η' extends η by mappings $\alpha \mapsto [\![\delta(\alpha)]\!]_\eta$ for all $\alpha \in \Delta'$. By the interpretation of operations, it remains to show $v \in [\![\tau_1]\!]_{\eta'}$ and $[\![\delta(\tau_2)]\!]_\eta = [\![\tau_2]\!]_{\eta'}$. Which follows immediately from lemma 12. □

Lemma 14 (Subtyping compatibility).

Proof. By induction on subtyping rules we will show that if $\Delta \vdash \sigma_1 <: \sigma_2$, then $[\![\sigma_1]\!]_\eta \subseteq [\![\sigma_2]\!]_\eta$ for all $\eta \in [\![\Delta]\!]$. Then, by lemma 6, from $\Delta \vdash \tau_1 <: \tau_2$, $\Delta \vdash \rho_1 <: \rho_2$ and $\Delta; \Gamma \models e : \tau_1 \;/\; \rho_1$ we will be able to conclude $\Delta; \Gamma \models e : \tau_2 \;/\; \rho_2$.

For the case of the reflexivity rule, we obviously have $[\![\sigma]\!]_\eta \subseteq [\![\sigma]\!]_\eta$.

For the case of the function type rule, assume $[\![\tau_2^1]\!]_\eta \subseteq [\![\tau_1^1]\!]_\eta$, $[\![\rho_1]\!]_\eta \subseteq [\![\rho_2]\!]_\eta$, and $[\![\tau_1^2]\!]_\eta \subseteq [\![\tau_2^2]\!]_\eta$. We want to show $[\![\tau_1^1 \to_{\rho_1} \tau_1^2]\!]_\eta \subseteq [\![\tau_2^1 \to_{\rho_2} \tau_2^2]\!]_\eta$. So take any $(\lambda x.\, e)$ in the former and any $v \in [\![\tau_2^1]\!]$. Since $v \in [\![\tau_1^1]\!]_\eta$, we have $e\{v/x\} \in \mathcal{E}[\![\tau_1^2/\rho_1]\!]_\eta$. By lemma 6 we obtain $e\{v/x\} \in \mathcal{E}[\![\tau_2^2/\rho_2]\!]_\eta$ as desired.

For the case of the universal quantifier rule, assume $[\![\tau_1]\!]_{\eta[\alpha\mapsto\mu]} \subseteq [\![\tau_2]\!]_{\eta[\alpha\mapsto\mu]}$ for all $\mu \in [\![\kappa]\!]$. The claim holds since

$$\begin{aligned}[\![\forall\alpha :: \kappa.\, \tau_1]\!]_\eta &= \{v \mid \forall\mu \in [\![\kappa]\!].\, v \in [\![\tau_1]\!]_{[\alpha\mapsto\mu]\eta}\} \\ &\subseteq \{v \mid \forall\mu \in [\![\kappa]\!].\, v \in [\![\tau_2]\!]_{[\alpha\mapsto\mu]\eta}\} = [\![\forall\alpha :: \kappa.\, \tau_2]\!]_\eta.\end{aligned}$$

The case of the empty row rule holds trivially, since $[\![\iota]\!]_\eta = \emptyset$.

For the case of the row extension rule, assume $[\![\rho_1]\!]_\eta \subseteq [\![\rho_2]\!]_\eta$. We clearly have

$$\{(v, n+1, \mu) \mid (v, n, \mu) \in [\![\rho_1]\!]_\eta\} \subseteq \{(v, n+1, \mu) \mid (v, n, \mu) \in [\![\rho_2]\!]_\eta\},$$

so $[\![\varepsilon \cdot \rho_1]\!]_\eta \subseteq [\![\varepsilon \cdot \rho_2]\!]_\eta$ as well. □

Lemma 15 (Polymorphism introduction compatibility)**.**

Proof. Assume $\Delta, \alpha :: \kappa; \models e : \tau \;/\; \iota$. Take $\eta \in [\![\Delta]\!]$. We know e evaluates to a value in $[\![\tau]\!]_{\eta[\alpha\mapsto\mu]}$ for any $\mu \in [\![\kappa]\!]$. Therefore this value is in $[\![\forall\alpha :: \kappa.\, \tau]\!]_\eta$, and by antireduction $e \in \mathcal{E}[\![\forall\alpha :: \kappa.\, \tau/\iota]\!]_\eta$. □

Lemma 16 (Polymorphism elimination compatibility)**.**

Proof. Assume $\Delta \vdash \sigma :: \kappa$ and $\Delta; \models e : \forall\alpha :: \kappa.\, \tau \;/\; \rho$. By lemma 12 we have $[\![\tau\{\sigma/\alpha\}]\!]_\eta = [\![\tau]\!]_{\eta[\alpha\mapsto[\![\sigma]\!]_\eta]}$, which is a superset of $[\![\forall\alpha :: \kappa.\, \tau]\!]$. So we have $\Delta; \models e : \tau\{\sigma/\alpha\} \;/\; \rho$ by lemma 6. □

Theorem 1 (Termination of evaluation)**.**

Proof. If $\vdash e : \tau/\iota$, then $e \in \mathcal{E}[\![\tau/\iota]\!]$ and e has to terminate to a value, since $[\![\iota]\!]$ is empty and hence $\mathcal{S}[\![\tau/\iota]\!]$ is empty. □

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