

プログラミング言語周りノート

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第 1 章

Preliminaries

1.1 基本的な表記

量子化 (quantifier) の束縛をコンマ (,) で続けて書く。束縛の終わりをピリオド (.) で示す。例えば,

$$\forall x_1 \in X_1, x_2 \in X_2. \exists y_1 \in Y_1, y_2 \in Y_2. x_1 = y_1 \wedge x_2 = y_2$$

は,

$$\forall x_1 \in X_1. \forall x_2 \in X_2. \exists y_1 \in Y_1. \exists y_2 \in Y_2. x_1 = y_1 \wedge x_2 = y_2$$

と等しい。また, 量子子の束縛において, *such that* を省略し, コンマ (,) で繋げて書く。例えば,

$$\forall x \in \{0, 1\}, x \neq 0. x = 1$$

は,

$$\forall x \in \{0, 1\}. x \neq 0 \implies x = 1$$

と等しい。また, \implies , \iff が他の記号と混同する場合, それぞれ *implies*, *iff* を使用する。

集合 (*set*) について, 以下の表記を用いる。

- 集合 A について, その濃度 (*cardinality*) を $|A|$ と表記する。なお, A が有限集合 (*finite set*) の時, 濃度とは要素の個数のことである。
- 集合 A について, $a \in A$ を $a : A$ と表記する。
- 自然数 (*natural number*) の集合を $\mathbb{N} = \{0, 1, \dots\}$ と表記する。また, n 以上の自然数の集合を $\mathbb{N}_{\geq n} = \{n, n+1, \dots\}$ と表記する。
- 自然数 $n \in \mathbb{N}$ について, $\{1, \dots, n\}$ を $[n]$ と表記する。
- 集合 A の冪集合を $\mathcal{P}(A) = \{X \mid X \subseteq A\}$, 有限冪集合を $\mathcal{P}_{fin}(A) = \{X \in \mathcal{P}(A) \mid X \text{ は有限集合}\}$ と表記する。
- 集合 A_1, \dots, A_n の直積 (*cartesian product*) を $A_1 \times \dots \times A_n = \{(a_1, \dots, a_n) \mid a_1 \in A_1, \dots, a_n \in A_n\}$ と表記する。集合 A の n 直積を $A^n = \underbrace{A \times \dots \times A}_{n \text{ 項}}$ と表記する。特に, $A^0 = \{\epsilon\}$ である。
- 集合 A_1, \dots, A_n の直和 (*disjoin union*) を $A_1 \uplus \dots \uplus A_n = (A_1 \times \{1\}) \cup \dots \cup (A_n \times \{n\})$ と表記する。なお, 文脈から明らかな場合, 直和の添字を省略し, $a \in A_i$ に対して, $a \in A_1 \uplus \dots \uplus A_n$ と表記する。
- 集合 A の B との差集合を $A \setminus B = \{a \in A \mid a \notin B\}$ と表記する。

集合 Σ について, $\bigcup_{n \in \mathbb{N}} \Sigma^n$ を Σ^* と表記する。この時, $\alpha \in \Sigma^*$ を Σ による列 (*sequence*) と呼ぶ。列について, 以下の表記を用いる。

- $(\sigma_1, \dots, \sigma_n) \in \Sigma^n$ について, $(\sigma_1, \dots, \sigma_n)$ を $\sigma_1 \dots \sigma_n$ と表記する。
- 列 $\alpha = \sigma_1 \dots \sigma_n \in \Sigma^*$ について, その長さを $|\alpha| = n$ と表記する。

集合 A, B について, $R \subseteq A \times B$ を関係 (*relation*) と呼ぶ。また,

$$A \rightarrow B \stackrel{\text{def}}{=} \{R \in \mathcal{P}(A \times B) \mid \forall x \in A, (x, y_1), (x, y_2) \in R. y_1 = y_2\}$$

という表記を導入し, 関係 $f : A \rightarrow B$ を A から B への部分関数 (*partial function*) と呼ぶ。さらに,

$$A \rightarrow B \stackrel{\text{def}}{=} \{f : A \rightarrow B \mid \forall x \in A. \exists y \in B. (x, y) \in f\}$$

という表記を導入し, 部分関数 $f : A \rightarrow B$ を (全) 関数 (*function*) と呼ぶ。関係について, 以下の表記を用いる。

- 関係 $R \subseteq A \times B$ について, $(a, b) \in R$ を $a R b$ と表記する。
- 関係 $R \subseteq A \times B$ について, 定義域 (*domain*) を $\text{dom}(R) = \{a \mid \exists b. (a, b) \in R\}$, 値域 (*range*) を $\text{cod}(R) = \{b \mid \exists a. (a, b) \in R\}$ と表記する。
- 部分関数 $f : A \rightarrow B$ について, $(a, b) \in f$ を $f(a) = b$ と表記する。

- 関係 $R_1 \subseteq A \times B$, $R_2 \subseteq B \times C$ について, その合成 (composition) を $R_1; R_2 = R_2 \circ R_1 = \{(x, z) \in A \times C \mid \exists y \in B. (x, y) \in R_1, (y, z) \in R_2\}$ と表記する.
- 関係 $R \subseteq A \times B$, 集合 $X \subseteq A$ について, R の X による制限 (restriction) を $R \upharpoonright_X = \{(a, b) \in R \mid a \in X\}$ と表記する. 特に関数 $f : A \rightarrow B$ の $X \subseteq A$ による制限は, 関数 $f \upharpoonright_X : X \rightarrow B$ になる.
- $a \in A$, $b \in B$ について, その組を $a \mapsto b = (a, b)$, 関数 $f : A \rightarrow B$ を $f = x \mapsto f(x)$ と表記する.
- 2 項関係 $R \subseteq A^2$ について, その推移閉包 (transitive closure), つまり以下を満たす最小の 2 項関係を $R^+ \subseteq A^2$ と表記する.
 - 任意の $(a, b) \in R$ について, $(a, b) \in R^+$.
 - 任意の $(a, b) \in R^+$, $(b, c) \in R^+$ について, $(a, c) \in R^+$.
- 2 項関係 $R \subseteq A^2$ について, その反射推移閉包 (reflexive transitive closure) を $R^* = R^+ \cup \{(a, a) \mid a \in A\}$ と表記する.

集合 I について, その要素で添字付けられた対象の列 $\{a_i\}_{i \in I}$ を I で添字づけられた族 (indexed family) と呼ぶ. 族について, 以下の表記を用いる.

- 族の集合を $\prod_{i \in I} A_i = \{\{a_i\}_{i \in I} \mid \forall i \in I, a_i \in A_i\}$ と表記する.
- 集合の族 $A = \{A_i\}_{i \in I}$ について, 次の条件を満たす時, A は互いに素 (pairwise disjoint) であるという.

$$\forall i_1, i_2 \in I, i_1 \neq i_2. A_{i_1} \cap A_{i_2} = \emptyset$$

第 2 章

Basic Calculus

2.1 WIP: (Untyped) λ -Calculus

2.2 Simply Typed λ -Calculus

Alias: STLC, λ^\rightarrow [GTL89]

2.2.1 Syntax

| | | | |
|----------|-----|-------------------------|-----------------|
| e | ::= | x | (variable) |
| | | $e e$ | (application) |
| | | $\lambda x : \tau. e$ | (abstraction) |
| | | c_A | (constant) |
| τ | ::= | A | (atomic type) |
| | | $\tau \rightarrow \tau$ | (function type) |
| Γ | ::= | \cdot | (empty) |
| | | $\Gamma, x : \tau$ | (cons) |

Convention:

$$\tau_1 \rightarrow \tau_2 \rightarrow \cdots \rightarrow \tau_n \stackrel{\text{def}}{=} \tau_1 \rightarrow (\tau_2 \rightarrow (\cdots \rightarrow \tau_n) \cdots)$$

$$e_1 e_2 \cdots e_n \stackrel{\text{def}}{=} (\cdots (e_1 e_2) \cdots) e_n$$

Environment Reference:

$$\boxed{\Gamma(x) = \tau}$$

$$\frac{x = x'}{(\Gamma, x' : \tau)(x) = \tau} \quad \frac{x \neq x' \quad \Gamma(x) = \tau}{(\Gamma, x' : \tau')(x) = \tau}$$

Free Variable:

$$\boxed{fv(e) = \{\bar{x}'\}}$$

$$\frac{}{fv(x) = \{x\}} \quad \frac{fv(e_1) = X_1 \quad fv(e_2) = X_2}{fv(e_1 e_2) = X_1 \cup X_2} \quad \frac{fv(e) = X}{fv(\lambda x : \tau. e) = X \setminus \{x\}} \quad \frac{}{fv(c_A) = \emptyset}$$

Substitution:

部分関数 $\{x_1 \mapsto e_1, \dots, x_n \mapsto e_n\}$ を, $[x_1 \leftarrow e_1, \dots, x_n \leftarrow e_n]$ または $[x_1, \dots, x_n \leftarrow e_1, \dots, e_n]$ と表記する.

$$\boxed{e[\bar{x}' \leftarrow \bar{e}'] = e''}$$

$$\frac{[\bar{x}' \leftarrow \bar{e}'](x) = e}{x[\bar{x}' \leftarrow \bar{e}'] = e} \quad \frac{x \notin \text{dom}([\bar{x}' \leftarrow \bar{e}'])}{x[\bar{x}' \leftarrow \bar{e}'] = x}$$

$$\frac{e_1[\bar{x}' \leftarrow \bar{e}'] = e_1'' \quad e_2[\bar{x}' \leftarrow \bar{e}'] = e_2''}{(e_1 e_2)[\bar{x}' \leftarrow \bar{e}'] = e_1'' e_2''} \quad \frac{e([\bar{x}' \leftarrow \bar{e}'] \upharpoonright_{\text{dom}([\bar{x}' \leftarrow \bar{e}']) \setminus \{x\}}) = e''}{(\lambda x : \tau. e)[\bar{x}' \leftarrow \bar{e}'] = \lambda x : \tau. e''} \quad \frac{}{c_A[\bar{x}' \leftarrow \bar{e}'] = c_A}$$

α -Equality:

$$\boxed{e_1 \equiv_\alpha e_2}$$

$$\frac{x_1 = x_2}{x_1 \equiv_\alpha x_2} \quad \frac{x' \notin fv(e_1) \cup fv(e_2) \quad e_1[x_1 \leftarrow x'] \equiv_\alpha e_2[x_2 \leftarrow x']}{\lambda x_1 : \tau. e_1 \equiv_\alpha \lambda x_2 : \tau. e_2} \quad \frac{e_1 \equiv_\alpha e_2 \quad e_1' \equiv_\alpha e_2'}{e_1 e_1' \equiv_\alpha e_2 e_2'} \quad \frac{}{c_A \equiv_\alpha c_A}$$

定理 1 (Correctness of Substitution). 式 e , 置換 $[\bar{x}' \leftarrow \bar{e}']$ について, $X = \text{dom}([\bar{x}' \leftarrow \bar{e}'])$ とした時,

$$fv(e[\bar{x}' \leftarrow \bar{e}']) = (fv(e) \setminus X) \cup \bigcup_{x \in fv(e) \cap X} fv([\bar{x}' \leftarrow \bar{e}'](x)).$$

□

定理 2 (α -Equality Does Not Touch Free Variables). $e_1 \equiv_{\alpha} e_2$ ならば, $fv(e_1) = fv(e_2)$.

□

2.2.2 Typing Semantics

$$\boxed{\Gamma \vdash e : \tau}$$

$$\begin{array}{c} \frac{\Gamma(x) = \tau}{\Gamma \vdash x : \tau} \text{ T-Var} \\ \frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2} \text{ T-Abs} \\ \frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau} \text{ T-App} \\ \frac{}{\Gamma \vdash c_A : A} \text{ T-Const} \end{array}$$

特に, $\cdot \vdash e : \tau$ の時, $e : \tau$ と表記.

2.2.3 Evaluation Semantics (Call-By-Value)

$$\begin{array}{lcl} v & ::= & \lambda x : \tau. e \\ & | & c_A \\ C & ::= & [] \\ & | & C e \\ & | & v C \end{array}$$

Small Step:

$$\boxed{e \Rightarrow e'}$$

$$\begin{array}{c} \overline{(\lambda x : \tau. e) v \Rightarrow e[x \leftarrow v]} \\ \frac{e \Rightarrow e'}{C[e] \Rightarrow C[e']} \end{array}$$

Big Step:

$$\boxed{e \Downarrow v}$$

$$\frac{e_1 \Downarrow \lambda x : \tau. e'_1 \quad e_2 \Downarrow v_2 \quad e'_1[x \leftarrow v_2] \Downarrow v}{e_1 e_2 \Downarrow v}$$

定理 3 (Adequacy of Small Step and Big Step). $e \Rightarrow^* v$ iff $e \Downarrow v$.

□

定理 4 (Type Soundness). $e : \tau$ の時, $e \Rightarrow^* v$, $e \Downarrow v$ となる $v = \text{nf}(\Rightarrow, e)$ が存在し,

- $\tau = \tau_1 \rightarrow \tau_2$ の時, $v \equiv_{\alpha} \lambda x' : \tau_1. e'$ となる $\lambda x' : \tau'. e'$ が存在する.
- $\tau = A$ の時, $v \equiv_{\alpha} c_A$ となる c_A が存在する.

□

2.2.4 Equational Reasoning

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\begin{array}{c}
\frac{\Gamma, x : \tau \vdash e_1 : \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash (\lambda x : \tau. e_1) e_2 \equiv e_1[x \leftarrow e_2] : \tau} \text{Eq-}\beta\text{-Lam} \quad \frac{x \notin \text{fv}(e) \quad \Gamma \vdash e : \tau_1 \rightarrow \tau_2}{\Gamma \vdash (\lambda x : \tau_1. e x) \equiv e : \tau_1 \rightarrow \tau_2} \text{Eq-}\eta\text{-Lam} \\
\frac{e_1 \equiv_{\alpha} e_2 \quad \Gamma \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-}\alpha\text{-Refl} \\
\frac{\Gamma \vdash e_2 \equiv e_1 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-Sym} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau \quad \Gamma \vdash e_2 \equiv e_3 : \tau}{\Gamma \vdash e_1 \equiv e_3 : \tau} \text{Eq-Trans} \\
\frac{\Gamma, x : \tau \vdash e_1 \equiv e_2 : \tau'}{\Gamma \vdash \lambda x : \tau. e_1 \equiv \lambda x : \tau. e_2 : \tau \rightarrow \tau'} \text{Eq-Cong-Abs} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau' \rightarrow \tau \quad \Gamma \vdash e'_1 \equiv e'_2 : \tau'}{\Gamma \vdash e_1 e'_1 \equiv e_2 e'_2 : \tau} \text{Eq-Cong-App}
\end{array}$$

特に, $\cdot \vdash e_1 \equiv e_2 : \tau$ の時, $e_1 \equiv e_2 : \tau$ と表記.

定理 5 (Respect Typing). $\Gamma \vdash e_1 \equiv e_2 : \tau$ ならば, $\Gamma \vdash e_1 : \tau$ かつ $\Gamma \vdash e_2 : \tau$. □

定理 6 (Respect Evaluation). $e_1 \equiv e_2 : \tau$ の時, $e'_1 \Rightarrow^* e_1$, $e_2 \Rightarrow^* e'_2$ ならば $e'_1 \equiv e'_2 : \tau$. □

系 7. $e_1 \equiv e_2 : \tau$ の時, $e_1 \Rightarrow^* e'_1$, $e_2 \Rightarrow^* e'_2$ ならば $e'_1 \equiv e'_2 : \tau$. □

証明. $e_1 \Rightarrow^* e_1$ より, 定理 6 から $e_1 \equiv e'_2 : \tau$. よって, T-Sym から $e'_2 \equiv e_1 : \tau$ であり, $e'_2 \Rightarrow^* e'_2$ より定理 6 から $e'_2 \equiv e'_1 : \tau$. 故に, T-Sym から $e'_1 \equiv e'_2 : \tau$. ■

2.3 WIP: System-T

2.4 WIP: PCF

2.5 System-F

Alias: F, Second Order Typed Lambda Calculus, $\lambda 2$ [GTL89]

2.5.1 Syntax

| | | |
|--------------|---------------------------|-------------------------|
| $e ::=$ | x | (variable) |
| | $ \lambda x : \tau. e$ | (abstraction) |
| | $ e e$ | (application) |
| | $ \Lambda t. e$ | (universal abstraction) |
| | $ e \tau$ | (universal application) |
| $\tau ::=$ | t | (type variable) |
| | $ \tau \rightarrow \tau$ | (function type) |
| | $ \forall t. \tau$ | (polymorphic type) |
| $\Gamma ::=$ | \cdot | (empty) |
| | $ \Gamma, x : \tau$ | (variable cons) |
| | $ \Gamma, t : \Omega$ | (type variable cons) |

Convention:

$$\begin{aligned} \tau_1 \rightarrow \tau_2 \rightarrow \cdots \rightarrow \tau_n &\stackrel{\text{def}}{=} \tau_1 \rightarrow (\tau_2 \rightarrow (\cdots \rightarrow \tau_n) \cdots) \\ e_1 e_2 \cdots e_n &\stackrel{\text{def}}{=} (\cdots (e_1 e_2) \cdots) e_n \end{aligned}$$

Environment Reference:

$$\boxed{\Gamma(x) = \tau}$$

$$\begin{array}{ccc} \frac{x = x'}{(\Gamma, x' : \tau)(x) = \tau} & \frac{x \neq x' \quad \Gamma(x) = \tau}{(\Gamma, x' : \tau')(x) = \tau} & \frac{\Gamma(x) = \tau}{(\Gamma, t : \Omega)(x) = \tau} \\ \frac{t = t'}{(\Gamma, t' : \Omega)(t) = \Omega} & \frac{t \neq t' \quad \Gamma(t) = \Omega}{(\Gamma, t' : \Omega')(t) = \Omega} & \frac{\Gamma(t) = \Omega}{(\Gamma, x : \tau)(t) = \Omega} \end{array}$$

Free Variable:

$$\boxed{fv(e) = \{\bar{x}\}}$$

$$\begin{array}{ccccc} \frac{}{fv(x) = \{x\}} & \frac{fv(e_1) = X_1 \quad fv(e_2) = X_2}{fv(e_1 e_2) = X_1 \cup X_2} & \frac{fv(e) = X}{fv(\lambda x : \tau. e) = X \setminus \{x\}} & \frac{fv(e) = X}{fv(e \tau) = X} & \frac{fv(e) = X}{fv(\Lambda t. e) = X} \end{array}$$

Substitution:

部分関数 $\{x_1 \mapsto e_1, \dots, x_n \mapsto e_n\}$ を, $[x_1 \leftarrow e_1, \dots, x_n \leftarrow e_n]$ または $[x_1, \dots, x_n \leftarrow e_1, \dots, e_n]$ と表記する.

$$\boxed{e[\bar{x}' \leftarrow \bar{e}'] = e''}$$

$$\begin{array}{ccc} \frac{[\bar{x}' \leftarrow \bar{e}'](x) = e}{x[\bar{x}' \leftarrow \bar{e}'] = e} & \frac{x \notin \text{dom}([\bar{x}' \leftarrow \bar{e}'])}{x[\bar{x}' \leftarrow \bar{e}'] = x} & \\ \frac{e_1[\bar{x}' \leftarrow \bar{e}'] = e_1'' \quad e_2[\bar{x}' \leftarrow \bar{e}'] = e_2''}{(e_1 e_2)[\bar{x}' \leftarrow \bar{e}'] = e_1'' e_2''} & \frac{e([\bar{x}' \leftarrow \bar{e}'] \upharpoonright_{\text{dom}([\bar{x}' \leftarrow \bar{e}']) \setminus \{x\}}) = e''}{(\lambda x : \tau. e)[\bar{x}' \leftarrow \bar{e}'] = \lambda x : \tau. e''} & \\ \frac{e[\bar{x}' \leftarrow \bar{e}'] = e''}{(e \tau)[\bar{x}' \leftarrow \bar{e}'] = e'' \tau} & \frac{e[\bar{x}' \leftarrow \bar{e}'] = e''}{(\Lambda t. e)[\bar{x}' \leftarrow \bar{e}'] = \Lambda t. e''} & \end{array}$$

Type Free Variable:

$$\boxed{tyfv(e) = \{\bar{x}\}}$$

$$\begin{array}{c} \overline{tyfv(x) = \emptyset} \quad \frac{tyfv(e_1) = T_1 \quad tyfv(e_2) = T_2}{tyfv(e_1 e_2) = T_1 \cup T_2} \quad \frac{tyfv(\tau) = T_1 \quad tyfv(e) = T_2}{tyfv(\lambda x : \tau. e) = T_1 \cup T_2} \\ \frac{tyfv(e) = T_1 \quad tyfv(\tau) = T_2}{tyfv(e \tau) = T_1 \cup T_2} \quad \frac{tyfv(e) = T}{tyfv(\Lambda t. e) = T \setminus \{t\}} \\ \overline{tyfv(t) = \{t\}} \quad \frac{tyfv(\tau_1) = T_1 \quad tyfv(\tau_2) = T_2}{tyfv(\tau_1 \rightarrow \tau_2) = T_1 \cup T_2} \quad \frac{tyfv(\tau) = T}{tyfv(\forall t. \tau) = T \setminus \{t\}} \end{array}$$

Type Substitution:

部分関数 $\{t_1 \mapsto \tau_1, \dots, t_n \mapsto \tau_n\}$ を, $[t_1 \leftarrow \tau_1, \dots, t_n \leftarrow \tau_n]$ または $[t_1, \dots, t_n \leftarrow \tau_1, \dots, \tau_n]$ と表記する.

$$\boxed{e[t \leftarrow \tau] = e'}$$

$$\begin{array}{c} \overline{x[t' \leftarrow \tau'] = x} \quad \frac{e_1[t' \leftarrow \tau'] = e'_1 \quad e_2[t' \leftarrow \tau'] = e'_2}{(e_1 e_2)[t' \leftarrow \tau'] = e'_1 e'_2} \quad \frac{\tau[t' \leftarrow \tau'] = \tau'' \quad e[t' \leftarrow \tau'] = e''}{(\lambda x : \tau. e)[t' \leftarrow \tau'] = \lambda x : \tau''. e''} \\ \frac{e[t' \leftarrow \tau'] = e'' \quad \tau[t' \leftarrow \tau'] = \tau''}{(e \tau)[t' \leftarrow \tau'] = e'' \tau''} \quad \frac{e([t' \leftarrow \tau'] \upharpoonright_{\text{dom}([t' \leftarrow \tau'] \setminus \{t\})}) = e''}{(\Lambda t. e)[t' \leftarrow \tau'] = \Lambda t. e''} \end{array}$$

$$\boxed{\tau[t' \leftarrow \tau'] = \tau''}$$

$$\begin{array}{c} \frac{[t' \leftarrow \tau'](t) = \tau}{t[t' \leftarrow \tau'] = \tau} \quad \frac{t \notin \text{dom}([t' \leftarrow \tau'])}{t[t' \leftarrow \tau'] = t} \quad \frac{\tau_1[t' \leftarrow \tau'] = \tau'_1 \quad \tau_2[t' \leftarrow \tau'] = \tau'_2}{(\tau_1 \rightarrow \tau_2)[t' \leftarrow \tau'] = \tau'_1 \rightarrow \tau'_2} \quad \frac{\tau([t' \leftarrow \tau'] \upharpoonright_{\text{dom}([t' \leftarrow \tau'] \setminus \{t\})}) = \tau''}{(\forall t. \tau)[t' \leftarrow \tau'] = \forall t. \tau''} \end{array}$$

α -Equality:

$$\boxed{e_1 \equiv_{\alpha} e_2}$$

$$\begin{array}{c} \frac{x_1 = x_2}{x_1 \equiv_{\alpha} x_2} \quad \frac{e_1 \equiv_{\alpha} e_2 \quad e'_1 \equiv_{\alpha} e'_2}{e_1 e'_1 \equiv_{\alpha} e_2 e'_2} \quad \frac{\tau_1 \equiv_{\alpha} \tau_2 \quad x' \notin f\upsilon(e_1) \cup f\upsilon(e_2) \quad e_1[x_1 \leftarrow x'] \equiv_{\alpha} e_2[x_2 \leftarrow x']}{\lambda x_1 : \tau_1. e_1 \equiv_{\alpha} \lambda x_2 : \tau_2. e_2} \\ \frac{e_1 \equiv_{\alpha} e_2 \quad \tau_1 \equiv_{\alpha} \tau_2}{e_1 \tau_1 \equiv_{\alpha} e_2 \tau_2} \quad \frac{t' \notin tyfv(e_1) \cup tyfv(e_2) \quad e_1[t_1 \leftarrow t'] \equiv_{\alpha} e_2[t_2 \leftarrow t']}{\Lambda t_1. e_1 \equiv_{\alpha} \Lambda t_2. e_2} \end{array}$$

$$\boxed{\tau_1 \equiv_{\alpha} \tau_2}$$

$$\frac{t_1 = t_2}{t_1 \equiv_{\alpha} t_2} \quad \frac{\tau_1 \equiv_{\alpha} \tau_2 \quad \tau'_1 \equiv_{\alpha} \tau'_2}{\tau_1 \rightarrow \tau'_1 \equiv_{\alpha} \tau_2 \rightarrow \tau'_2} \quad \frac{t' \notin tyfv(\tau_1) \cup tyfv(\tau_2) \quad \tau_1[t_1 \leftarrow t'] \equiv_{\alpha} \tau_2[t_2 \leftarrow t']}{\forall t_1. \tau_1 \equiv_{\alpha} \forall t_2. \tau_2}$$

定理 8 (Correctness of Substitution). 置換 $[\bar{x}' \leftarrow \bar{e}']$ について, $X = \text{dom}([\bar{x}' \leftarrow \bar{e}'])$ とした時,

$$f\upsilon(e[\bar{x}' \leftarrow \bar{e}']) = (f\upsilon(e) \setminus X) \cup \bigcup_{x \in f\upsilon(e) \cap X} f\upsilon([\bar{x}' \leftarrow \bar{e}'])(x).$$

□

定理 9 (Correctness of Type Substitution). 式 e , 型 τ , 型置換 $[\bar{t}' \leftarrow \bar{\tau}']$ について, $T = \text{dom}([\bar{t}' \leftarrow \bar{\tau}'])$ とした時,

$$\begin{array}{c} tyfv(e[\bar{t}' \leftarrow \bar{\tau}']) = (tyfv(e) \setminus T) \cup \bigcup_{t \in tyfv(e) \cap T} tyfv([\bar{t}' \leftarrow \bar{\tau}'])(t) \\ tyfv(\tau[\bar{t}' \leftarrow \bar{\tau}']) = (tyfv(\tau) \setminus T) \cup \bigcup_{t \in tyfv(\tau) \cap T} tyfv([\bar{t}' \leftarrow \bar{\tau}'])(t). \end{array}$$

□

定理 10 (α -Equality Does Not Touch Free Variables).

- $\tau_1 \equiv_{\alpha} \tau_2$ ならば $tyfu(\tau_1) = tyfu(\tau_2)$.
- $e_1 \equiv_{\alpha} e_2$ ならば, $fv(e_1) = fv(e_2)$, $tyfu(e_1) = tyfu(e_2)$.

□

2.5.2 Typing Semantics

$$\boxed{\Gamma \vdash e : \tau}$$

$$\begin{array}{c}
 \frac{\Gamma(x) = \tau}{\Gamma \vdash x : \tau} \text{ T-Var} \\
 \frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2} \text{ T-Abs} \\
 \frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau} \text{ T-App} \\
 \frac{\Gamma, t : \Omega \vdash e : \tau}{\Gamma \vdash \Lambda t. e : \forall t. \tau} \text{ T-UnivAbs} \\
 \frac{\Gamma \vdash e : \forall t. \tau_1}{\Gamma \vdash e \tau_2 : \tau_1[t \leftarrow \tau_2]} \text{ T-UnivApp} \\
 \frac{\Gamma \vdash \tau \equiv_{\alpha} \tau' : \Omega \quad \Gamma \vdash e : \tau'}{\Gamma \vdash e : \tau} \text{ T-}\alpha\text{-Equiv}
 \end{array}$$

特に, $\cdot \vdash e : \tau$ の時, $e : \tau$ と表記.

2.5.3 Evaluation Semantics (Call-By-Value)

$$\begin{array}{lcl}
 v & ::= & \lambda x : \tau. e \\
 & | & \Lambda t. e \\
 C & ::= & [] \\
 & | & C e \\
 & | & v C \\
 & | & C \tau
 \end{array}$$

Small Step:

$$\boxed{e \Rightarrow e'}$$

$$\begin{array}{c}
 \overline{(\lambda x : \tau. e) v \Rightarrow e[x \leftarrow v]} \\
 \overline{(\Lambda t. e) \tau \Rightarrow e[t \leftarrow \tau]} \\
 \frac{e \Rightarrow e'}{C[e] \Rightarrow C[e']}
 \end{array}$$

Big Step:

$$\boxed{e \Downarrow v}$$

$$\begin{array}{c}
 \frac{e_1 \Downarrow \lambda x : \tau. e'_1 \quad e_2 \Downarrow v_2 \quad e'_1[x \leftarrow v_2] \Downarrow v}{e_1 e_2 \Downarrow v} \\
 \frac{e \Downarrow \Lambda t. e'_1 \quad e'_1[t \leftarrow \tau] \Downarrow v}{e \tau \Downarrow v}
 \end{array}$$

定理 11 (Adequacy of Small Step and Big Step). $e \Rightarrow^* v$ iff $e \Downarrow v$.

□

定理 12 (Type Soundness). $e : \tau$ の時, $e \Rightarrow^* v$, $e \Downarrow v$ となる $v = \text{nf}(\Rightarrow, e)$ が存在し,

- $\tau = \tau_1 \rightarrow \tau_2$ の時, $v \equiv_\alpha \lambda x' : \tau_1. e'$ となる $\lambda x' : \tau_1. e'$ が存在する.
- $\tau = \forall t. \tau_1$ の時, $v \equiv_\alpha \Lambda t. e'$ となる $\Lambda t. e'$ が存在する.

□

2.5.4 Equational Reasoning

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\begin{array}{c} \frac{\Gamma, x : \tau_2 \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash (\lambda x : \tau_2. e_1) e_2 \equiv e_1[x \leftarrow e_2] : \tau} \text{Eq-}\beta\text{-Lam} \quad \frac{x \notin \text{fv}(e) \quad \Gamma \vdash e : \tau_1 \rightarrow \tau_2}{\Gamma \vdash (\lambda x : \tau_1. e x) \equiv e : \tau_1 \rightarrow \tau_2} \text{Eq-}\eta\text{-Lam} \\ \frac{\Gamma, t : \Omega \vdash e : \tau}{\Gamma \vdash (\Lambda t. e) \tau_2 \equiv e[t \leftarrow \tau_2] : \tau[t \leftarrow \tau_2]} \text{Eq-}\beta\text{-UnivLam} \quad \frac{t \notin \text{tyfv}(e) \quad \Gamma \vdash e : \forall t'. \tau}{\Gamma \vdash (\Lambda t. e t) \equiv e : \forall t'. \tau} \text{Eq-}\eta\text{-UnivLam} \\ \frac{e_1 \equiv_\alpha e_2 \quad \Gamma \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-}\alpha\text{-Refl} \quad \frac{\tau \equiv_\alpha \tau' \quad \Gamma \vdash e_1 \equiv e_2 : \tau'}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-}\alpha\text{-Type} \\ \frac{\Gamma \vdash e_2 \equiv e_1 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-Sym} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau \quad \Gamma \vdash e_2 \equiv e_3 : \tau}{\Gamma \vdash e_1 \equiv e_3 : \tau} \text{Eq-Trans} \\ \frac{\Gamma, x : \tau \vdash e_1 \equiv e_2 : \tau'}{\Gamma \vdash \lambda x : \tau. e_1 \equiv \lambda x : \tau. e_2 : \tau \rightarrow \tau'} \text{Eq-Cong-Abs} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau' \rightarrow \tau \quad \Gamma \vdash e'_1 \equiv e'_2 : \tau'}{\Gamma \vdash e_1 e'_1 \equiv e_2 e'_2 : \tau} \text{Eq-Cong-App} \\ \frac{\Gamma, t : \Omega \vdash e_1 \equiv e_2 : \tau}{\Gamma \vdash \Lambda t. e_1 \equiv \Lambda t. e_2 : \forall(t. \tau)} \text{Eq-Cong-UnivAbs} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \forall t. \tau}{\Gamma \vdash e_1 \tau' \equiv e_2 \tau' : \tau[t \leftarrow \tau']} \text{Eq-Cong-UnivApp} \end{array}$$

特に, $\cdot \vdash e_1 \equiv e_2 : \tau$ の時, $e_1 \equiv e_2 : \tau$ と表記.

定理 13 (Respect Typing). $\Gamma \vdash e_1 \equiv e_2 : \tau$ ならば, $\Gamma \vdash e_1 : \tau$ かつ $\Gamma \vdash e_2 : \tau$. □

定理 14 (Respect Evaluation). $e_1 \equiv e_2 : \tau$ の時, $e'_1 \Rightarrow^* e_1$, $e_2 \Rightarrow^* e'_2$ ならば $e'_1 \equiv e'_2 : \tau$. □

系 15. $e_1 \equiv e_2 : \tau$ の時, $e_1 \Rightarrow^* e'_1$, $e_2 \Rightarrow^* e'_2$ ならば $e'_1 \equiv e'_2 : \tau$. □

証明. $e_1 \Rightarrow^* e_1$ より, 定理 14 から $e_1 \equiv e'_2 : \tau$. よって, T-Sym から $e'_2 \equiv e_1 : \tau$ であり, $e'_2 \Rightarrow^* e'_2$ より定理 14 から $e'_2 \equiv e'_1 : \tau$. 故に, T-Sym から $e'_1 \equiv e'_2 : \tau$. ■

2.5.5 Definability

Product

Product of τ_1 and τ_2 :

$$\begin{aligned} \tau_1 \times \tau_2 &\stackrel{\text{def}}{=} \forall t. (\tau_1 \rightarrow \tau_2 \rightarrow t) \rightarrow t \\ \langle e_1, e_2 \rangle &\stackrel{\text{def}}{=} \Lambda t. \lambda x : \tau_1 \rightarrow \tau_2 \rightarrow t. x e_1 e_2 \\ \pi_1 e &\stackrel{\text{def}}{=} e \tau_1 \lambda x_1. \lambda x_2. x_1 \\ \pi_2 e &\stackrel{\text{def}}{=} e \tau_2 \lambda x_1. \lambda x_2. x_2 \end{aligned}$$

Admissible typing rule:

$$\boxed{\Gamma \vdash e : \tau}$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash \langle e_1, e_2 \rangle : \tau_1 \times \tau_2} \text{T-Product} \quad \frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \pi_1 e : \tau_1} \text{T-Proj-1} \quad \frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \pi_2 e : \tau_2} \text{T-Proj-2}$$

Admissible equality:

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash \pi_1 \langle e_1, e_2 \rangle \equiv e_1 : \tau_1} \text{Eq-}\beta\text{-Product-1} \quad \frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash \pi_2 \langle e_1, e_2 \rangle \equiv e_2 : \tau_2} \text{Eq-}\beta\text{-Product-2}$$

$$\frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \langle \pi_1 e, \pi_2 e \rangle \equiv e : \tau_1 \times \tau_2} \text{Eq-}\eta\text{-Product}$$

Existential Type

Existence of $\exists t. \tau$:

$$\begin{aligned} \exists t. \tau &\stackrel{\text{def}}{=} \forall t'. (\forall t. \tau \rightarrow t') \rightarrow t' \\ \text{pack} \langle \tau_t, e \rangle &\stackrel{\text{def}}{=} \Lambda t'. \lambda x : (\forall t. \tau \rightarrow t'). x \tau_t e \\ \text{unpack} \langle t, x \rangle = e_1. \tau_2. e_2 &\stackrel{\text{def}}{=} e_1 \tau_2 (\Lambda t. \lambda x : \tau. e_2) \end{aligned}$$

Admissible typing rule:

$$\boxed{\Gamma \vdash e : \tau}$$

$$\frac{\Gamma \vdash e : \tau[t \leftarrow \tau_t]}{\Gamma \vdash \text{pack} \langle \tau_t, e \rangle : \exists t. \tau} \text{T-Pack} \quad \frac{\Gamma \vdash e_1 : \exists t. \tau \quad \Gamma, t : \Omega, x : \tau \vdash e_2 : \tau_2 \quad t \notin \text{tyfu}(\tau_2)}{\Gamma \vdash \text{unpack} \langle t, x \rangle = e_1. \tau_2. e_2 : \tau_2} \text{T-Unpack}$$

Admissible equality:

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\frac{\Gamma \vdash e_1 : \tau_1[t \leftarrow \tau_t] \quad \Gamma, t : \Omega, x : \tau_1 \vdash e_2 : \tau_2 \quad t \notin \text{tyfu}(\tau_2)}{\Gamma \vdash \text{unpack} \langle t, x \rangle = \text{pack} \langle \tau_t, e_1 \rangle. \tau_2. e_2 \equiv e_2[t \leftarrow \tau_t][x \leftarrow e_1] : \tau_2} \text{Eq-}\beta\text{-Exist}$$

$$\frac{\Gamma \vdash e : \exists t'. \tau \quad \tau' \equiv_{\alpha} \exists t'. \tau}{\Gamma \vdash \text{unpack} \langle t, x \rangle = e. \tau'. \text{pack} \langle t, x \rangle \equiv e : \exists t'. \tau} \text{Eq-}\eta\text{-Exist}$$

2.5.6 Typability

[Wel99]

TODO

2.6 System-F ω

Alias: F ω , $\lambda\omega$ [RRD14]

2.6.1 Syntax

| | | |
|--------------|-------------------------------|-------------------------|
| $e ::=$ | x | (variable) |
| | $ \lambda x : \tau. e$ | (abstraction) |
| | $ e e$ | (application) |
| | $ \Lambda t : \kappa. e$ | (universal abstraction) |
| | $ e \tau$ | (universal application) |
| $\tau ::=$ | t | (type variable) |
| | $ \tau \rightarrow \tau$ | (function type) |
| | $ \forall t : \kappa. \tau$ | (polymorphic type) |
| | $ \lambda t : \kappa. \tau$ | (type abstraction) |
| | $ \tau \tau$ | (type application) |
| $\kappa ::=$ | Ω | (type kind) |
| | $ \kappa \rightarrow \kappa$ | (arrow kind) |
| $\Gamma ::=$ | \cdot | (empty) |
| | $ \Gamma, x : \tau$ | (variable cons) |
| | $ \Gamma, t : \kappa$ | (type variable cons) |

Convention:

$$\tau_1 \rightarrow \tau_2 \rightarrow \dots \rightarrow \tau_n \stackrel{\text{def}}{=} \tau_1 \rightarrow (\tau_2 \rightarrow (\dots \rightarrow \tau_n) \dots)$$

$$e_1 e_2 \dots e_n \stackrel{\text{def}}{=} (\dots (e_1 e_2) \dots) e_n$$

Environment Reference:

$$\boxed{\Gamma(x) = \tau}$$

$$\frac{x = x'}{(\Gamma, x' : \tau)(x) = \tau} \quad \frac{x \neq x' \quad \Gamma(x) = \tau}{(\Gamma, x' : \tau')(x) = \tau} \quad \frac{\Gamma(x) = \tau}{(\Gamma, t : \kappa)(x) = \tau}$$

$$\frac{t = t'}{(\Gamma, t' : \kappa)(t) = \kappa} \quad \frac{t \neq t' \quad \Gamma(t) = \kappa}{(\Gamma, t' : \kappa')(t) = \kappa} \quad \frac{\Gamma(t) = \kappa}{(\Gamma, x : \tau)(t) = \kappa}$$

Free Variable:

$$\boxed{fv(e) = \{\bar{x}\}}$$

$$\frac{}{fv(x) = \{x\}} \quad \frac{fv(e) = X}{fv(\lambda x : \tau. e) = X \setminus \{x\}} \quad \frac{fv(e_1) = X_1 \quad fv(e_2) = X_2}{fv(e_1 e_2) = X_1 \cup X_2} \quad \frac{fv(e) = X}{fv(\Lambda t : \kappa. e) = X} \quad \frac{fv(e) = X}{fv(e \tau) = X}$$

Substitution:

部分関数 $\{x_1 \mapsto e_1, \dots, x_n \mapsto e_n\}$ を, $[x_1 \leftarrow e_1, \dots, x_n \leftarrow e_n]$ または $[x_1, \dots, x_n \leftarrow e_1, \dots, e_n]$ と表記する.

$$\boxed{e[\bar{x}' \leftarrow \bar{e}'] = e''}$$

$$\frac{\frac{\bar{x}' \leftarrow \bar{e}'](x) = e}{x[\bar{x}' \leftarrow \bar{e}'] = e} \quad \frac{x \notin \text{dom}([\bar{x}' \leftarrow \bar{e}'])}{x[\bar{x}' \leftarrow \bar{e}'] = x}}{e([\bar{x}' \leftarrow \bar{e}'] \upharpoonright_{\text{dom}([\bar{x}' \leftarrow \bar{e}']) \setminus \{x\}}) = e''} \quad \frac{e_1[\bar{x}' \leftarrow \bar{e}'] = e'_1 \quad e_2[\bar{x}' \leftarrow \bar{e}'] = e'_2}{(e_1 e_2)[\bar{x}' \leftarrow \bar{e}'] = e'_1 e'_2}$$

$$\frac{e([\bar{x}' \leftarrow \bar{e}'] \upharpoonright_{\text{dom}([\bar{x}' \leftarrow \bar{e}']) \setminus \{x\}}) = e''}{(\lambda x : \tau. e)[\bar{x}' \leftarrow \bar{e}'] = \lambda x : \tau. e''}$$

$$\frac{e[\overline{x'} \leftarrow \overline{e'}] = e''}{(\Lambda t : \kappa. e)[\overline{x'} \leftarrow \overline{e'}] = \Lambda t : \kappa. e''} \quad \frac{e[\overline{x'} \leftarrow \overline{e'}] = e''}{(e \tau)[\overline{x'} \leftarrow \overline{e'}] = e'' \tau}$$

Type Free Variable:

$$\boxed{tyfv(e) = \{\bar{t}\}}$$

$$\frac{}{tyfv(x) = \emptyset} \quad \frac{tyfv(\tau) = T_1 \quad tyfv(e) = T_2}{tyfv(\lambda x : \tau. e) = T_1 \cup T_2} \quad \frac{tyfv(e_1) = T_1 \quad tyfv(e_2) = T_2}{tyfv(e_1 e_2) = T_1 \cup T_2}$$

$$\frac{tyfv(e) = T}{tyfv(\Lambda t : \kappa. e) = T \setminus \{t\}} \quad \frac{tyfv(e) = T_1 \quad tyfv(\tau) = T_2}{tyfv(e \tau) = T_1 \cup T_2}$$

$$\boxed{tyfv(\tau) = \{\bar{t}\}}$$

$$\frac{}{tyfv(t) = \{t\}} \quad \frac{tyfv(\tau_1) = T_1 \quad tyfv(\tau_2) = T_2}{tyfv(\tau_1 \rightarrow \tau_2) = T_1 \cup T_2} \quad \frac{tyfv(\tau) = T}{tyfv(\forall t : \kappa. \tau) = T \setminus \{t\}}$$

$$\frac{tyfv(\tau) = T}{tyfv(\lambda t : \kappa. \tau) = T \setminus \{t\}} \quad \frac{tyfv(\tau_1) = T_1 \quad tyfv(\tau_2) = T_2}{tyfv(\tau_1 \tau_2) = T_1 \cup T_2}$$

Type Substitution:

部分関数 $\{t_1 \mapsto \tau_1, \dots, t_n \mapsto \tau_n\}$ を, $[t_1 \leftarrow \tau_1, \dots, t_n \leftarrow \tau_n]$ または $[t_1, \dots, t_n \leftarrow t_1, \dots, t_n]$ と表記する.

$$\boxed{e[\bar{t}' \leftarrow \bar{\tau}'] = e'}$$

$$\frac{}{x[\bar{t}' \leftarrow \bar{\tau}'] = x} \quad \frac{e_1[\bar{t}' \leftarrow \bar{\tau}'] = e'_1 \quad e_2[\bar{t}' \leftarrow \bar{\tau}'] = e'_2}{(e_1 e_2)[\bar{t}' \leftarrow \bar{\tau}'] = e'_1 e'_2} \quad \frac{\tau[\bar{t}' \leftarrow \bar{\tau}'] = \tau'' \quad e[\bar{t}' \leftarrow \bar{\tau}'] = e''}{(\lambda x : \tau. e)[\bar{t}' \leftarrow \bar{\tau}'] = \lambda x : \tau''. e''}$$

$$\frac{e[\bar{t}' \leftarrow \bar{\tau}'] = e'' \quad \tau[\bar{t}' \leftarrow \bar{\tau}'] = \tau''}{(e \tau)[\bar{t}' \leftarrow \bar{\tau}'] = e'' \tau''} \quad \frac{e([\bar{t}' \leftarrow \bar{\tau}'] \upharpoonright_{\text{dom}([\bar{t}' \leftarrow \bar{\tau}'] \setminus \{t\})}) = e''}{(\Lambda t : \kappa. e)[\bar{t}' \leftarrow \bar{\tau}'] = \Lambda t : \kappa. e''}$$

$$\boxed{\tau[\bar{t}' \leftarrow \bar{\tau}'] = \tau''}$$

$$\frac{[\bar{t}' \leftarrow \bar{\tau}'](t) = \tau}{t[\bar{t}' \leftarrow \bar{\tau}'] = \tau} \quad \frac{t \notin \text{dom}([\bar{t}' \leftarrow \bar{\tau}'])}{t[\bar{t}' \leftarrow \bar{\tau}'] = t}$$

$$\frac{\tau_1[\bar{t}' \leftarrow \bar{\tau}'] = \tau_1'' \quad \tau_2[\bar{t}' \leftarrow \bar{\tau}'] = \tau_2''}{(\tau_1 \rightarrow \tau_2)[\bar{t}' \leftarrow \bar{\tau}'] = \tau_1'' \rightarrow \tau_2''} \quad \frac{\tau([\bar{t}' \leftarrow \bar{\tau}'] \upharpoonright_{\text{dom}([\bar{t}' \leftarrow \bar{\tau}'] \setminus \{t\})}) = \tau''}{(\forall t : \kappa. \tau)[\bar{t}' \leftarrow \bar{\tau}'] = \forall t : \kappa. \tau''}$$

$$\frac{\tau([\bar{t}' \leftarrow \bar{\tau}'] \upharpoonright_{\text{dom}([\bar{t}' \leftarrow \bar{\tau}'] \setminus \{t\})}) = \tau''}{(\lambda t : \kappa. \tau)[\bar{t}' \leftarrow \bar{\tau}'] = \lambda t : \kappa. \tau''} \quad \frac{\tau_1[\bar{t}' \leftarrow \bar{\tau}'] = \tau_1'' \quad \tau_2[\bar{t}' \leftarrow \bar{\tau}'] = \tau_2''}{(\tau_1 \tau_2)[\bar{t}' \leftarrow \bar{\tau}'] = \tau_1'' \tau_2''}$$

α -Equality:

$$\boxed{e_1 \equiv_{\alpha} e_2}$$

$$\frac{x_1 = x_2}{x_1 \equiv_{\alpha} x_2} \quad \frac{e_1 \equiv_{\alpha} e_2 \quad e'_1 \equiv_{\alpha} e'_2}{e_1 e'_1 \equiv_{\alpha} e_2 e'_2} \quad \frac{\tau_1 \equiv_{\alpha} \tau_2 \quad x' \notin fv(e_1) \cup fv(e_2) \quad e_1[x_1 \leftarrow x'] \equiv_{\alpha} e_2[x_2 \leftarrow x']}{\lambda x_1 : \tau_1. e_1 \equiv_{\alpha} \lambda x_2 : \tau_2. e_2}$$

$$\frac{e_1 \equiv_{\alpha} e_2 \quad \tau_1 \equiv_{\alpha} \tau_2}{e_1 \tau_1 \equiv_{\alpha} e_2 \tau_2} \quad \frac{t' \notin tyfv(e_1) \cup tyfv(e_2) \quad e_1[t_1 \leftarrow t'] \equiv_{\alpha} e_2[t_2 \leftarrow t']}{\Lambda t_1 : \kappa. e_1 \equiv_{\alpha} \Lambda t_2 : \kappa. e_2}$$

$$\boxed{\tau_1 \equiv_{\alpha} \tau_2}$$

$$\frac{t_1 = t_2}{t_1 \equiv_{\alpha} t_2} \quad \frac{\tau_1 \equiv_{\alpha} \tau_2 \quad \tau'_1 \equiv_{\alpha} \tau'_2}{\tau_1 \rightarrow \tau'_1 \equiv_{\alpha} \tau_2 \rightarrow \tau'_2} \quad \frac{t' \notin tyfv(\tau_1) \cup tyfv(\tau_2) \quad \tau_1[t_1 \leftarrow t'] \equiv_{\alpha} \tau_2[t_2 \leftarrow t']}{\forall t_1 : \kappa. \tau_1 \equiv_{\alpha} \forall t_2 : \kappa. \tau_2}$$

$$\frac{t' \notin tyfv(\tau_1) \cup tyfv(\tau_2) \quad \tau_1[t_1 \leftarrow t'] \equiv_{\alpha} \tau_2[t_2 \leftarrow t']}{\lambda t_1 : \kappa. \tau_1 \equiv_{\alpha} \lambda t_2 : \kappa. \tau_2} \quad \frac{\tau_1 \equiv_{\alpha} \tau_2 \quad \tau'_1 \equiv_{\alpha} \tau'_2}{\tau_1 \tau'_1 \equiv_{\alpha} \tau_2 \tau'_2}$$

定理 16 (Correctness of Substitution). 置換 $[\bar{x}' \leftarrow \bar{e}']$ について, $X = \text{dom}([\bar{x}' \leftarrow \bar{e}'])$ とした時,

$$fv(e[\bar{x}' \leftarrow \bar{e}']) = (fv(e) \setminus X) \cup \bigcup_{x \in fv(e) \cap X} fv([\bar{x}' \leftarrow \bar{e}'](x)).$$

□

定理 17 (Correctness of Type Substitution). 式 e , 型 τ , 型置換 $[\bar{t}' \leftarrow \bar{\tau}']$ について, $T = \text{dom}([\bar{t}' \leftarrow \bar{\tau}'])$ とした時,

$$\begin{aligned} tyfv(e[\bar{t}' \leftarrow \bar{\tau}']) &= (tyfv(e) \setminus T) \cup \bigcup_{t \in tyfv(e) \cap T} tyfv([\bar{t}' \leftarrow \bar{\tau}'](t)) \\ tyfv(\tau[\bar{t}' \leftarrow \bar{\tau}']) &= (tyfv(\tau) \setminus T) \cup \bigcup_{t \in tyfv(\tau) \cap T} tyfv([\bar{t}' \leftarrow \bar{\tau}'](t)). \end{aligned}$$

□

定理 18 (α -Equality Does Not Touch Free Variables).

- $\tau_1 \equiv_\alpha \tau_2$ ならば $tyfv(\tau_1) = tyfv(\tau_2)$.
- $e_1 \equiv_\alpha e_2$ ならば, $fv(e_1) = fv(e_2)$, $tyfv(e_1) = tyfv(e_2)$.

□

2.6.2 Typing Semantics

Kinding:

$$\boxed{\Gamma \vdash \tau : \kappa}$$

$$\begin{aligned} & \frac{\Gamma(t) = \kappa}{\Gamma \vdash t : \kappa} \text{K-Var} \\ & \frac{\Gamma \vdash \tau_1 : \Omega \quad \Gamma \vdash \tau_2 : \Omega}{\Gamma \vdash \tau_1 \rightarrow \tau_2 : \Omega} \text{K-Arrow} \\ & \frac{\Gamma, t : \kappa \vdash \tau : \Omega}{\Gamma \vdash \forall t : \kappa. \tau : \Omega} \text{K-Forall} \\ & \frac{\Gamma, t : \kappa_1 \vdash \tau : \kappa_2}{\Gamma \vdash \lambda t : \kappa_1. \tau : \kappa_1 \rightarrow \kappa_2} \text{K-Abs} \\ & \frac{\Gamma \vdash \tau_1 : \kappa_2 \rightarrow \kappa \quad \Gamma \vdash \tau_2 : \kappa_2}{\Gamma \vdash \tau_1 \tau_2 : \kappa} \text{K-App} \end{aligned}$$

Type equivalence:

$$\boxed{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}$$

$$\begin{aligned} & \frac{\Gamma, t : \kappa_2 \vdash \tau_1 : \kappa \quad \Gamma \vdash \tau_2 : \kappa_2}{\Gamma \vdash (\lambda t : \kappa_2. \tau_1) \tau_2 \equiv \tau_1[t \leftarrow \tau_2] : \kappa} \text{T-Eq-}\beta\text{-Lam} & \frac{t \notin tyfv(\tau) \quad \Gamma \vdash \tau : \kappa_1 \rightarrow \kappa_2}{\Gamma \vdash (\lambda t : \kappa_1. \tau) t \equiv \tau : \kappa_1 \rightarrow \kappa_2} \text{T-Eq-}\eta\text{-Lam} \\ & \frac{\tau_1 \equiv_\alpha \tau_2 \quad \Gamma \vdash \tau_1 : \kappa \quad \Gamma \vdash \tau_2 : \kappa}{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa} \text{T-Eq-}\alpha\text{-Refl} \\ & \frac{\Gamma \vdash \tau_2 \equiv \tau_1 : \kappa}{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa} \text{T-Eq-Sym} & \frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa \quad \Gamma \vdash \tau_2 \equiv \tau_3 : \kappa}{\Gamma \vdash \tau_1 \equiv \tau_3 : \kappa} \text{T-Eq-Trans} \\ & \frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \Omega \quad \Gamma \vdash \tau'_1 \equiv \tau'_2 : \Omega}{\Gamma \vdash \tau_1 \rightarrow \tau'_1 \equiv \tau_2 \rightarrow \tau'_2 : \Omega} \text{T-Eq-Cong-Arrow} & \frac{\Gamma, t : \kappa \vdash \tau_1 \equiv \tau_2 : \Omega}{\Gamma \vdash \forall t : \kappa. \tau_1 \equiv \forall t : \kappa. \tau_2 : \Omega} \text{Eq-Cong-Forall} \\ & \frac{\Gamma, t : \kappa \vdash \tau_1 \equiv \tau_2 : \kappa'}{\Gamma \vdash \lambda t : \kappa. \tau_1 \equiv \lambda t : \kappa. \tau_2 : \kappa \rightarrow \kappa'} \text{T-Eq-Cong-Abs} & \frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa' \rightarrow \kappa \quad \Gamma \vdash \tau'_1 \equiv \tau'_2 : \kappa'}{\Gamma \vdash \tau_1 \tau'_1 \equiv \tau_2 \tau'_2 : \kappa} \text{Eq-Cong-App} \end{aligned}$$

定理 19 (Respect Kinding). $\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa$ ならば, $\Gamma \vdash \tau_1 : \kappa$ かつ $\Gamma \vdash \tau_2 : \kappa$.

□

Typing:

$$\boxed{\Gamma \vdash e : \tau}$$

$$\begin{array}{c} \frac{\Gamma \vdash \tau : \Omega \quad \Gamma(x) = \tau}{\Gamma \vdash x : \tau} \text{ T-Var} \\ \frac{\Gamma \vdash \tau_1 : \Omega \quad \Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2} \text{ T-Abs} \\ \frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau} \text{ T-App} \\ \frac{\Gamma, t : \kappa \vdash e : \tau}{\Gamma \vdash \Lambda t : \kappa. e : \forall t : \kappa. \tau} \text{ T-UnivAbs} \\ \frac{\Gamma \vdash e : \forall t : \kappa. \tau_1 \quad \Gamma \vdash \tau_2 : \kappa}{\Gamma \vdash e \tau_2 : \tau_1[t \leftarrow \tau_2]} \text{ T-UnivApp} \\ \frac{\Gamma \vdash \tau \equiv \tau' : \Omega \quad \Gamma \vdash e : \tau'}{\Gamma \vdash e : \tau} \text{ T-Equiv} \end{array}$$

特に, $\cdot \vdash e : \tau$ の時, $e : \tau$ と表記.

定理 20 (Respect Type Kind). $\Gamma \vdash e : \tau$ ならば, $\Gamma \vdash \tau : \Omega$.

□

2.6.3 Evaluation Semantics (Call-By-Value)

$$\begin{array}{lcl} v & ::= & \lambda x : \tau. e \\ & | & \Lambda t : \kappa. e \\ C & ::= & [] \\ & | & C e \\ & | & v C \\ & | & C \tau \end{array}$$

Small Step:

$$\boxed{e \Rightarrow e'}$$

$$\begin{array}{c} \overline{(\lambda x : \tau. e) v \Rightarrow e[x \leftarrow v]} \\ \overline{(\Lambda t : \kappa. e) \tau \Rightarrow e[t \leftarrow \tau]} \\ \frac{e \Rightarrow e'}{C[e] \Rightarrow C[e']} \end{array}$$

Big Step:

$$\boxed{e \Downarrow v}$$

$$\begin{array}{c} \frac{e_1 \Downarrow \lambda x : \tau. e'_1 \quad e_2 \Downarrow v_2 \quad e'_1[x \leftarrow v_2] \Downarrow v}{e_1 e_2 \Downarrow v} \\ \frac{e \Downarrow \Lambda t : \kappa. e'_1 \quad e'_1[t \leftarrow \tau] \Downarrow v}{e \tau \Downarrow v} \end{array}$$

定理 21 (Adequacy of Small Step and Big Step). $e \Rightarrow^* v$ iff $e \Downarrow v$.

□

定理 22 (Type Soundness). $e : \tau$ の時, $e \Rightarrow^* v$, $e \Downarrow v$ となる $v = \text{nf}(\Rightarrow, e)$ が存在し,

- $\tau = \tau_1 \rightarrow \tau_2$ の時, $v \equiv_{\alpha} \lambda x' : \tau_1. e'$ となる $\lambda x' : \tau_1. e'$ が存在する.
- $\tau = \forall t : \kappa. \tau_1$ の時, $v \equiv_{\alpha} \Lambda t : \kappa. e'$ となる $\Lambda t : \kappa. e'$ が存在する.

□

2.6.4 Equational Reasoning

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\begin{array}{c}
\frac{\Gamma, x : \tau_2 \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash (\lambda x : \tau_2. e_1) e_2 \equiv e_1[x \leftarrow e_2] : \tau} \text{Eq-}\beta\text{-Lam} \quad \frac{x \notin \text{fv}(e) \quad \Gamma \vdash e : \tau_1 \rightarrow \tau_2}{\Gamma \vdash (\lambda x : \tau_1. e) x \equiv e : \tau_1 \rightarrow \tau_2} \text{Eq-}\eta\text{-Lam} \\
\frac{\Gamma, t : \kappa \vdash e : \tau}{\Gamma \vdash (\Lambda t : \kappa. e) \tau_2 \equiv e[t \leftarrow \tau_2] : \tau[t \leftarrow \tau_2]} \text{Eq-}\beta\text{-UnivLam} \quad \frac{t \notin \text{tyfv}(e) \quad \Gamma \vdash e : \forall t : \kappa. \tau}{\Gamma \vdash (\Lambda t : \kappa. e) t \equiv e : \forall t : \kappa. \tau} \text{Eq-}\eta\text{-UnivLam} \\
\frac{e_1 \equiv_{\alpha} e_2 \quad \Gamma \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-}\alpha\text{-Refl} \quad \frac{\tau \equiv_{\alpha} \tau' \quad \Gamma \vdash e_1 \equiv e_2 : \tau'}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-}\alpha\text{-Type} \\
\frac{\Gamma \vdash e_2 \equiv e_1 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \text{Eq-Sym} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau \quad \Gamma \vdash e_2 \equiv e_3 : \tau}{\Gamma \vdash e_1 \equiv e_3 : \tau} \text{Eq-Trans} \\
\frac{\Gamma, x : \tau \vdash e_1 \equiv e_2 : \tau'}{\Gamma \vdash \lambda x : \tau. e_1 \equiv \lambda x : \tau. e_2 : \tau \rightarrow \tau'} \text{Eq-Cong-Abs} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau' \rightarrow \tau \quad \Gamma \vdash e'_1 \equiv e'_2 : \tau'}{\Gamma \vdash e_1 e'_1 \equiv e_2 e'_2 : \tau} \text{Eq-Cong-App} \\
\frac{\Gamma, t : \kappa \vdash e_1 \equiv e_2 : \tau}{\Gamma \vdash \Lambda t : \kappa. e_1 \equiv \Lambda t : \kappa. e_2 : (\forall t : \kappa. \tau)} \text{Eq-Cong-UnivAbs} \\
\frac{\Gamma \vdash e_1 \equiv e_2 : \forall t : \kappa. \tau \quad \Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}{\Gamma \vdash e_1 \tau_1 \equiv e_2 \tau_2 : \tau[t \leftarrow \tau_1]} \text{Eq-Cong-UnivApp}
\end{array}$$

特に, $\cdot \vdash e_1 \equiv e_2 : \tau$ の時, $e_1 \equiv e_2 : \tau$ と表記.

定理 23 (Respect Typing). $\Gamma \vdash e_1 \equiv e_2 : \tau$ ならば, $\Gamma \vdash e_1 : \tau$ かつ $\Gamma \vdash e_2 : \tau$. □

定理 24 (Respect Evaluation). $e_1 \equiv e_2 : \tau$ の時, $e'_1 \Rightarrow^* e_1$, $e_2 \Rightarrow^* e'_2$ ならば $e'_1 \equiv e'_2 : \tau$. □

系 25. $e_1 \equiv e_2 : \tau$ の時, $e_1 \Rightarrow^* e'_1$, $e_2 \Rightarrow^* e'_2$ ならば $e'_1 \equiv e'_2 : \tau$. □

証明. $e_1 \Rightarrow^* e_1$ より, 定理 14 から $e_1 \equiv e'_2 : \tau$. よって, T-Sym から $e'_2 \equiv e_1 : \tau$ であり, $e'_2 \Rightarrow^* e'_2$ より定理 14 から $e'_2 \equiv e'_1 : \tau$. 故に, T-Sym から $e'_1 \equiv e'_2 : \tau$. ■

2.6.5 Definability

Product

Product of τ_1 and τ_2 :

$$\begin{aligned}
\tau_1 \times \tau_2 &\stackrel{\text{def}}{=} \forall t : \Omega. (\tau_1 \rightarrow \tau_2 \rightarrow t) \rightarrow t \\
\langle e_1, e_2 \rangle &\stackrel{\text{def}}{=} \Lambda t : \Omega. \lambda x : \tau_1 \rightarrow \tau_2 \rightarrow t. x e_1 e_2 \\
\pi_1 e &\stackrel{\text{def}}{=} e \tau_1 \lambda x_1. \lambda x_2. x_1 \\
\pi_2 e &\stackrel{\text{def}}{=} e \tau_2 \lambda x_1. \lambda x_2. x_2
\end{aligned}$$

Admissible kinding:

$$\boxed{\Gamma \vdash \tau : \kappa}$$

$$\frac{\Gamma \vdash \tau_1 : \Omega \quad \Gamma \vdash \tau_2 : \Omega}{\Gamma \vdash \tau_1 \times \tau_2 : \Omega} \text{T-Product}$$

Admissible type equality:

$$\boxed{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}$$

$$\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \Omega \quad \Gamma \vdash \tau'_1 \equiv \tau'_2 : \Omega}{\Gamma \vdash \tau_1 \times \tau'_1 \equiv \tau_2 \times \tau'_2 : \Omega} \text{ T-Eq-Product}$$

Admissible typing:

$$\boxed{\Gamma \vdash e : \tau}$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash \langle e_1, e_2 \rangle : \tau_1 \times \tau_2} \text{ T-Product} \quad \frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \pi_1 e : \tau_1} \text{ T-Prodj-1} \quad \frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \pi_2 e : \tau_2} \text{ T-Prodj-2}$$

Admissible equality:

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash \pi_1 \langle e_1, e_2 \rangle \equiv e_1 : \tau_1} \text{ Eq-}\beta\text{-Product-1} \quad \frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash \pi_2 \langle e_1, e_2 \rangle \equiv e_2 : \tau_2} \text{ Eq-}\beta\text{-Product-2}$$

$$\frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \langle \pi_1 e, \pi_2 e \rangle \equiv e : \tau_1 \times \tau_2} \text{ Eq-}\eta\text{-Product}$$

Existential Type

Existence of $\exists t : \kappa. \tau$:

$$\begin{aligned} \exists t : \kappa. \tau &\stackrel{\text{def}}{=} \forall t' : \Omega. (\forall t : \kappa. \tau \rightarrow t') \rightarrow t' \\ \text{pack}\langle \tau_t, e \rangle_{\exists t : \kappa. \tau} &\stackrel{\text{def}}{=} \Lambda t' : \Omega. \lambda x : (\forall t : \kappa. \tau \rightarrow t'). x \tau_t e \\ \text{unpack}\langle t : \kappa, x : \tau \rangle &= e_1. \tau_2. e_2 \stackrel{\text{def}}{=} e_1 \tau_2 (\Lambda t : \kappa. \lambda x : \tau. e_2) \end{aligned}$$

Admissible kinding:

$$\boxed{\Gamma \vdash \tau : \kappa}$$

$$\frac{\Gamma, t : \kappa \vdash \tau : \Omega}{\Gamma \vdash \exists t : \kappa. \tau : \Omega} \text{ T-Exist}$$

Admissible type equality:

$$\boxed{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}$$

$$\frac{\Gamma, t : \kappa \vdash \tau_1 \equiv \tau_2 : \Omega}{\Gamma \vdash \exists t : \kappa. \tau_1 \equiv \exists t : \kappa. \tau_2 : \Omega} \text{ T-Eq-Cong-Exist}$$

Admissible typing rule:

$$\boxed{\Gamma \vdash e : \tau}$$

$$\frac{\Gamma, t : \kappa \vdash \tau : \Omega \quad \Gamma \vdash \tau_t : \kappa \quad \Gamma \vdash e : \tau[t \leftarrow \tau_t]}{\Gamma \vdash \text{pack}\langle \tau_t, e \rangle_{\exists t : \kappa. \tau} : \exists t : \kappa. \tau} \text{ T-Pack}$$

$$\frac{\Gamma \vdash e_1 : \exists t : \kappa. \tau \quad \Gamma, t : \kappa, x : \tau \vdash e_2 : \tau_2 \quad t \notin \text{tyfv}(\tau_2)}{\Gamma \vdash \text{unpack}\langle t : \kappa, x : \tau \rangle = e_1. \tau_2. e_2 : \tau_2} \text{ T-Unpack}$$

Admissible equality:

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\begin{array}{c}
\frac{\Gamma \vdash \tau_t : \kappa \quad \Gamma \vdash e_1 : \tau_1[t \leftarrow \tau_t] \quad \Gamma, t : \kappa, x : \tau_1 \vdash e_2 : \tau_2 \quad t \notin \text{tyfv}(\tau_2)}{\Gamma \vdash \text{unpack}\langle t : \kappa, x : \tau_1 \rangle = \text{pack}\langle \tau_t, e_1 \rangle_{\exists t : \kappa. \tau_1}. \tau_2. e_2 \equiv e_2[t \leftarrow \tau_t][x \leftarrow e_1] : \tau_2} \text{Eq-}\beta\text{-Exist} \\
\frac{\Gamma \vdash e : (\exists t : \kappa. \tau) \quad \tau' \equiv \exists t : \kappa. \tau}{\Gamma \vdash \text{unpack}\langle t : \kappa, x : \tau \rangle = e. \tau'. \text{pack}\langle t, x \rangle_{\exists t : \kappa. \tau} \equiv e : (\exists t : \kappa. \tau)} \text{Eq-}\eta\text{-Exist}
\end{array}$$

2.7 $\lambda \mu$ -Calculus

Alias: $\lambda \mu$ [Sel01][Roc05]

2.7.1 Syntax

| | | |
|--------------|-------------------------|--------------------|
| $\tau ::=$ | t | (type variable) |
| | \top | (top type) |
| | $\tau \times \tau$ | (product type) |
| | $\tau \rightarrow \tau$ | (function type) |
| | \perp | (bottom type) |
| $e ::=$ | x | (variable) |
| | $\langle \rangle$ | (top value) |
| | $\langle e, e \rangle$ | (product) |
| | $\pi_1 e$ | (left projection) |
| | $\pi_2 e$ | (right projection) |
| | $\lambda x : \tau. e$ | (abstraction) |
| | $e e$ | (application) |
| | $[\alpha]e$ | (naming) |
| | $\mu \alpha : \tau. e$ | (un-naming) |
| $\Gamma ::=$ | \cdot | |
| | $\Gamma, x : \tau$ | |
| $\Delta ::=$ | \cdot | |
| | $\alpha : \tau, \Delta$ | |

Environment Reference:

$$\boxed{\Gamma(x) = \tau}$$

$$\frac{x = x'}{(\Gamma, x' : \tau)(x) = \tau} \quad \frac{x \neq x' \quad \Gamma(x) = \tau}{(\Gamma, x' : \tau')(x) = \tau}$$

$$\boxed{\Delta(\alpha) = \tau}$$

$$\frac{\alpha = \alpha'}{(\alpha' : \tau, \Delta)(\alpha) = \tau} \quad \frac{\alpha \neq \alpha' \quad \Delta(\alpha) = \tau}{(\alpha' : \tau', \Delta)(\alpha) = \tau}$$

2.7.2 Typing Semantics

$$\boxed{\Gamma \vdash e : \tau \mid \Delta}$$

$$\begin{array}{c} \frac{\Gamma(x) = \tau}{\Gamma \vdash x : \tau \mid \Delta} \text{ T-Var} \\ \frac{}{\Gamma \vdash \langle \rangle : \top \mid \Delta} \text{ T-Top} \\ \frac{\Gamma \vdash e_1 : \tau_1 \mid \Delta \quad \Gamma \vdash e_2 : \tau_2 \mid \Delta}{\Gamma \vdash \langle e_1, e_2 \rangle : \tau_1 \times \tau_2 \mid \Delta} \text{ T-Product} \\ \frac{\Gamma \vdash e : \tau_1 \times \tau_2 \mid \Delta}{\Gamma \vdash \pi_1 e : \tau_1 \mid \Delta} \text{ T-Proj-1} \\ \frac{\Gamma \vdash e : \tau_1 \times \tau_2 \mid \Delta}{\Gamma \vdash \pi_2 e : \tau_2 \mid \Delta} \text{ T-Proj-2} \\ \frac{\Gamma, x : \tau_1 \vdash e : \tau_2 \mid \Delta}{\Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2 \mid \Delta} \text{ T-Abs} \end{array}$$

$$\begin{array}{c}
\frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \mid \Delta \quad \Gamma \vdash e_2 : \tau_2 \mid \Delta}{\Gamma \vdash e_1 e_2 : \tau \mid \Delta} \text{ T-App} \\
\frac{\Delta(\alpha) = \tau \quad \Gamma \vdash e : \tau \mid \Delta}{\Gamma \vdash [\alpha]e : \perp \mid \Delta} \text{ T-Name} \\
\frac{\Gamma \vdash e : \perp \mid \alpha : \tau, \Delta}{\Gamma \vdash (\mu\alpha : \tau. e) : \tau \mid \Delta} \text{ T-Unname}
\end{array}$$

2.7.3 Equivalence

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau \mid \Delta}$$

$$\begin{array}{c}
\frac{\Gamma, x : \tau_2 \vdash e_1 : \tau \mid \Delta \quad \Gamma \vdash e_2 : \tau_2 \mid \Delta}{\Gamma \vdash (\lambda x : \tau_2. e_1) e_2 \equiv e_1[x \leftarrow e_2] : \tau \mid \Delta} \text{ Eq-}\beta\text{-Lam} \\
\frac{x \notin fv(e) \quad \Gamma \vdash e : \tau_1 \rightarrow \tau_2 \mid \Delta}{\Gamma \vdash (\lambda x : \tau_1. e x) \equiv e : \tau_1 \rightarrow \tau_2 \mid \Delta} \text{ Eq-}\eta\text{-Lam} \\
\frac{\Gamma \vdash e : \top \mid \Delta}{\Gamma \vdash \langle \rangle \equiv e : \top \mid \Delta} \text{ Eq-}\eta\text{-Top} \\
\frac{\Gamma \vdash e_1 : \tau_1 \mid \Delta \quad \Gamma \vdash e_2 : \tau_2 \mid \Delta}{\Gamma \vdash \pi_1 \langle e_1, e_2 \rangle \equiv e_1 : \tau_1 \mid \Delta} \text{ Eq-}\beta\text{-Product-1} \\
\frac{\Gamma \vdash e_1 : \tau_1 \mid \Delta \quad \Gamma \vdash e_2 : \tau_2 \mid \Delta}{\Gamma \vdash \pi_2 \langle e_1, e_2 \rangle \equiv e_2 : \tau_2 \mid \Delta} \text{ Eq-}\beta\text{-Product-2} \\
\frac{\Gamma \vdash e : \tau_1 \times \tau_2 \mid \Delta}{\Gamma \vdash \langle \pi_1 e, \pi_2 e \rangle \equiv e : \tau_1 \times \tau_2 \mid \Delta} \text{ Eq-}\eta\text{-Product} \\
\frac{\alpha_1 \notin fv(e) \quad \Gamma \vdash e : \perp \mid \alpha : \tau_1 \times \tau_2, \Delta}{\Gamma \vdash \pi_1(\mu\alpha : \tau_1 \times \tau_2. e) \equiv \mu\alpha_1 : \tau_1. e[[\alpha](-) \leftarrow [\alpha_1](\pi_1(-))]] : \tau_1 \mid \Delta} \text{ Eq-}\zeta\text{-Product-1} \\
\frac{\alpha_2 \notin fv(e) \quad \Gamma \vdash e : \perp \mid \alpha : \tau_1 \times \tau_2, \Delta}{\Gamma \vdash \pi_2(\mu\alpha : \tau_1 \times \tau_2. e) \equiv \mu\alpha_2 : \tau_2. e[[\alpha](-) \leftarrow [\alpha_2](\pi_2(-))]] : \tau_2 \mid \Delta} \text{ Eq-}\zeta\text{-Product-2} \\
\frac{\Gamma \vdash e : \perp \mid \alpha_2 : \tau_\alpha, \Delta}{\Gamma \vdash [\alpha_1](\mu\alpha_2 : \tau_\alpha. e) \equiv e[\alpha_2 \leftarrow \alpha_1] : \perp \mid \Delta} \text{ Eq-}\beta\text{-Mu} \\
\frac{\Gamma \vdash e : \tau \mid \Delta}{\Gamma \vdash (\mu\alpha : \tau. [\alpha]e) \equiv e : \tau \mid \Delta} \text{ Eq-}\eta\text{-Mu} \\
\frac{\alpha_2 \notin fv(e_1) \cup fv(e_2) \quad \Gamma \vdash e_1 : \perp \mid \alpha : \tau_1 \rightarrow \tau_2, \Delta \quad \Gamma \vdash e_2 : \tau_2 \mid \Delta}{\Gamma \vdash (\mu\alpha : \tau_1 \rightarrow \tau_2. e_1) e_2 \equiv \mu\alpha_2 : \tau_2. e_1[[\alpha](-) \leftarrow [\alpha_2]((-) e_2)]] : \tau_2 \mid \Delta} \text{ Eq-}\zeta\text{-Mu}
\end{array}$$

2.7.4 Elaboration (Call-By-Value)

$$\boxed{\Gamma \vdash e : \tau \rightsquigarrow e'}$$

$$\begin{array}{c}
\frac{\Gamma(x_{x_0}) = V_\tau}{\Gamma \vdash x_0 : \tau \rightsquigarrow \lambda x_k : K_\tau. x_k x_{x_0}} \\
\frac{}{\Gamma \vdash \langle \rangle : \top \rightsquigarrow \lambda x_k : K_\top. x_k \langle \rangle} \\
\frac{\Gamma \vdash e_1 : \tau_1 \rightsquigarrow e'_1 \quad \Gamma \vdash e_2 : \tau_2 \rightsquigarrow e'_2}{\Gamma \vdash \langle e_1, e_2 \rangle : \tau_1 \times \tau_2 \rightsquigarrow \lambda x_k : K_{\tau_1 \times \tau_2}. e'_1 (\lambda x_1 : V_{\tau_1}. e'_2 (\lambda x_2 : V_{\tau_2}. x_k \langle x_1, x_2 \rangle))} \\
\frac{\Gamma \vdash e : \tau_1 \times \tau_2 \rightsquigarrow e'}{\Gamma \vdash \pi_1 e : \tau_1 \rightsquigarrow \lambda x_k : K_{\tau_1}. e' (\lambda x : V_{\tau_1} \times V_{\tau_2}. x_k (\pi_1 x))} \\
\frac{\Gamma \vdash e : \tau_1 \times \tau_2 \rightsquigarrow e'}{\Gamma \vdash \pi_2 e : \tau_2 \rightsquigarrow \lambda x_k : K_{\tau_2}. e' (\lambda x : V_{\tau_1} \times V_{\tau_2}. x_k (\pi_2 x))} \\
\frac{\Gamma, x_{x_0} : V_{\tau_1} \vdash e : \tau_2 \rightsquigarrow e'}{\Gamma \vdash (\lambda x_0 : \tau_1. e) : \tau_1 \rightarrow \tau_2 \rightsquigarrow \lambda x_k : K_{\tau_1 \rightarrow \tau_2}. x_k (\lambda x : V_{\tau_1} \times K_{\tau_2}. (\lambda x_{x_0} : V_{\tau_1}. e') (\pi_1 x) (\pi_2 x))}
\end{array}$$

$$\begin{array}{c}
\frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \rightsquigarrow e'_1 \quad \Gamma \vdash e_2 : \tau_2 \rightsquigarrow e'_2}{\Gamma \vdash e_1 e_2 : \tau \rightsquigarrow \lambda x_k : K_\tau. e'_1 (\lambda x_1 : V_{\tau_2 \rightarrow \tau}. e'_2 (\lambda x_2 : V_{\tau_2}. x_1 \langle x_2, x_k \rangle))} \\
\frac{\Gamma, x_\alpha : K_\tau \vdash e : \perp \rightsquigarrow e'}{\Gamma \vdash (\mu \alpha : \tau. e) : \tau \rightsquigarrow \lambda x_\alpha : K_\tau. e' (\lambda x : \perp. \text{case } x \{ \})} \\
\frac{\Gamma(x_\alpha) = K_\tau \quad \Gamma \vdash e : \tau \rightsquigarrow e'}{\Gamma \vdash [\alpha]e : \tau \rightsquigarrow \lambda x_k : K_\perp. e' x_\alpha}
\end{array}$$

$$\boxed{V_\tau = \tau'}$$

$$\begin{array}{c}
\overline{V_\tau = \tau} \\
\frac{V_{\tau_1} = \tau'_1 \quad V_{\tau_2} = \tau'_2}{\overline{V_{\tau_1 \times \tau_2} = V_{\tau'_1} \times V_{\tau'_2}}} \\
\frac{V_{\tau_1} = \tau'_1 \quad K_{\tau_2} = \tau'_2}{\overline{V_{\tau_1 \rightarrow \tau_2} = \tau'_1 \times \tau'_2 \rightarrow R}} \\
\overline{V_\perp = \perp}
\end{array}$$

Abbreviation:

$$\begin{array}{l}
K_\tau \stackrel{\text{def}}{=} V_\tau \rightarrow R \\
C_\tau \stackrel{\text{def}}{=} K_\tau \rightarrow R
\end{array}$$

定理 26. $\Gamma \vdash e : \tau \rightsquigarrow e'$ ならば, $\Gamma \vdash e' : C_\tau$. □

定理 27. $\Gamma \vdash e : \tau \mid \Delta \iff V(\Gamma), K(\Delta) \vdash e : \tau \rightsquigarrow e'$. ただし,

$$\begin{array}{l}
V(\Gamma) \stackrel{\text{def}}{=} \begin{cases} V(\Gamma'), x_{x'} : V_{\tau'} & (\Gamma = \Gamma', x' : \tau') \\ \cdot & (\Gamma = \cdot) \end{cases} \\
K(\Delta) \stackrel{\text{def}}{=} \begin{cases} x_\alpha : K_\tau, K(\Delta') & (\Delta = \alpha : \tau, \Delta') \\ \cdot & (\Delta = \cdot) \end{cases} .
\end{array}$$

□

2.7.5 Elaboration (Call-By-Name)

$$\boxed{\Gamma \vdash e : \tau \rightsquigarrow e'}$$

$$\begin{array}{c}
\frac{\Gamma(x_{x_0}) = C_\tau}{\Gamma \vdash x_0 : \tau \rightsquigarrow \lambda x_k : K_\tau. x_{x_0} x_k} \\
\frac{\Gamma \vdash \langle \rangle : \top \rightsquigarrow \lambda x_k : \perp. \text{case } x_k \{ \}}{\Gamma \vdash e_1 : \tau_1 \rightsquigarrow e'_1 \quad \Gamma \vdash e_2 : \tau_2 \rightsquigarrow e'_2} \\
\frac{\Gamma \vdash \langle e_1, e_2 \rangle : \tau_1 \times \tau_2 \rightsquigarrow \lambda x_k : K_{\tau_1} + K_{\tau_2}. \text{case } x_k \{ x_{k_1}. e'_1 x_{k_1} \mid x_{k_2}. e'_2 x_{k_2} \}}{\Gamma \vdash e : \tau_1 \times \tau_2 \rightsquigarrow e'} \\
\frac{\Gamma \vdash \pi_1 e : \tau_1 \rightsquigarrow \lambda x_k : K_{\tau_1}. e' (i_1 x_k)}{\Gamma, x_{x_1} : C_{\tau_1} \vdash e : \tau_2 \rightsquigarrow e'} \\
\frac{\Gamma \vdash (\lambda x_1 : \tau_1. e) : \tau_1 \rightarrow \tau_2 \rightsquigarrow \lambda x_k : C_{\tau_1} \times K_{\tau_2}. e' [x_{x_1} \leftarrow \pi_1 x_k] (\pi_2 x_k)}{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \rightsquigarrow e'_1 \quad \Gamma \vdash e_2 : \tau_2 \rightsquigarrow e'_2} \\
\frac{\Gamma \vdash e_1 e_2 : \tau \rightsquigarrow \lambda x_k : K_\tau. e'_1 \langle e'_2, x_k \rangle}{\Gamma(x_\alpha) = K_\tau \quad \Gamma \vdash e : \tau \rightsquigarrow e'} \\
\frac{\Gamma \vdash [\alpha]e : \perp \rightsquigarrow \lambda x_k : K_\perp. e' x_\alpha}{\Gamma, x_\alpha : K_\tau \vdash e : \perp \rightsquigarrow e'} \\
\frac{\Gamma, x_\alpha : K_\tau \vdash e : \perp \rightsquigarrow e'}{\Gamma \vdash (\mu \alpha : \tau. e) : \tau \rightsquigarrow \lambda x_\alpha : K_\tau. e' \langle \rangle}
\end{array}$$

$$\boxed{K_\tau = \tau'}$$

$$\begin{array}{c} \overline{K_\top = \perp} \\ \frac{K_{\tau_1} = \tau'_1 \quad K_{\tau_2} = \tau'_2}{K_{\tau_1 \times \tau_2} = \tau'_1 + \tau'_2} \\ \frac{C_{\tau_1} = \tau'_1 \quad K_{\tau_2} = \tau'_2}{K_{\tau_1 \rightarrow \tau_2} = \tau'_1 \times \tau'_2} \\ \overline{K_\perp = \top} \end{array}$$

Abbreviation:

$$C_\tau \stackrel{\text{def}}{=} K_\tau \rightarrow R$$

定理 28. $\Gamma \vdash e : \tau \rightsquigarrow e'$ ならば, $\Gamma \vdash e' : C_\tau$. □

定理 29. $\Gamma \vdash e : \tau \mid \Delta \iff C(\Gamma), K(\Delta) \vdash e : \tau \rightsquigarrow e'$. ただし,

$$\begin{aligned} C(\Gamma) &\stackrel{\text{def}}{=} \begin{cases} C(\Gamma'), x_{x'} : C_{\tau'} & (\Gamma = \Gamma', x' : \tau') \\ \cdot & (\Gamma = \cdot) \end{cases} \\ K(\Delta) &\stackrel{\text{def}}{=} \begin{cases} x_\alpha : K_\tau, K(\Delta') & (\Delta = \alpha : \tau, \Delta') \\ \cdot & (\Delta = \cdot) \end{cases} . \end{aligned}$$

□

2.8 WIP: Lambda Bar Mu Mu Tilde Calculus

$\bar{\lambda} \mu \tilde{\mu}$ -Calculus

2.9 WIP: π -Calculus

第 3 章

Basic Algorithms

3.1 Martelli-Montanari Algorithm

[MM82]

$$\begin{array}{c}
 \overline{\mathcal{U}(x, x) = \emptyset} \\
 \overline{x_1 \neq x_2} \\
 \overline{\mathcal{U}(x_1, x_2) = \{x_1 \mapsto x_2\}} \\
 \overline{\mathcal{U}(f(a_1, \dots, a_n), f(b_1, \dots, b_n)) = \bigcup_{1 \leq i \leq n} \mathcal{U}(a_i, b_i)} \\
 \overline{x \notin \text{fv}(f(a_1, \dots, a_n))} \\
 \overline{\mathcal{U}(x, f(a_1, \dots, a_n)) = \{x \mapsto f(a_1, \dots, a_n)\}} \\
 \overline{x \notin \text{fv}(f(a_1, \dots, a_n))} \\
 \overline{\mathcal{U}(f(a_1, \dots, a_n), x) = \{x \mapsto f(a_1, \dots, a_n)\}}
 \end{array}$$

第 4 章

Modules and Phase Distinction

4.1 Light-Weight F-ing modules

[RRD14]

4.1.1 Internal Language

Having same power as System F ω

Syntax:

$$\begin{aligned}
 \kappa &::= \Omega \mid \kappa \rightarrow \kappa \\
 \tau &::= t \mid \tau \rightarrow \tau \mid \overline{\{l : \tau\}} \mid \forall t : \kappa. \tau \mid \exists t : \kappa. \tau \mid \lambda t : \kappa. \tau \mid \tau \tau \\
 e &::= x \mid \lambda x : \tau. e \mid e e \mid \overline{\{l = e\}} \mid e.l \mid \Lambda t : \kappa. e \mid e \tau \mid \text{pack}\langle \tau, e \rangle_\tau \mid \text{unpack}\langle t : \kappa, x : \tau \rangle = e \text{ in } e \\
 \Gamma &::= \cdot \mid \Gamma, t : \kappa \mid \Gamma, x : \tau
 \end{aligned}$$

Abbreviation:

$$\begin{aligned}
 \Sigma.l &\stackrel{\text{def}}{=} \begin{cases} (\Sigma.l).\bar{l}' & (\bar{l} = l \bar{l}') \\ \Sigma & (\bar{l} = \epsilon) \end{cases} \\
 \bar{\tau}_1 \rightarrow \bar{\tau}_2 &\stackrel{\text{def}}{=} \begin{cases} \tau_1 \rightarrow (\bar{\tau}_1' \rightarrow \tau_2) & (\bar{\tau}_1 = \tau_1 \bar{\tau}_1') \\ \tau_2 & (\bar{\tau}_1 = \epsilon) \end{cases} \\
 \lambda \overline{x : \tau}. e &\stackrel{\text{def}}{=} \begin{cases} \lambda x : \tau. \lambda \overline{x' : \tau'}. e & (\overline{x : \tau} = x : \tau \overline{x' : \tau'}) \\ e & (\overline{x : \tau} = \epsilon) \end{cases} \\
 e_0 \bar{e}_1 &\stackrel{\text{def}}{=} \begin{cases} e_0 e_1 \bar{e}_1' & (\bar{e}_1 = e_1 \bar{e}_1') \\ e_0 & (\bar{e}_1 = \epsilon) \end{cases} \\
 \forall \overline{t : \kappa}. \tau &\stackrel{\text{def}}{=} \begin{cases} \forall t : \kappa. \forall \overline{t' : \kappa'}. \tau & (\overline{t : \kappa} = t : \kappa \overline{t' : \kappa'}) \\ \tau & (\overline{t : \kappa} = \epsilon) \end{cases} \\
 \Lambda \overline{t : \kappa}. e &\stackrel{\text{def}}{=} \begin{cases} \Lambda t : \kappa. \Lambda \overline{t' : \kappa'}. e & (\overline{t : \kappa} = t : \kappa \overline{t' : \kappa'}) \\ e & (\overline{t : \kappa} = \epsilon) \end{cases} \\
 e \bar{\tau} &\stackrel{\text{def}}{=} \begin{cases} e \tau \bar{\tau}' & (\bar{\tau} = \tau \bar{\tau}') \\ e & (\bar{\tau} = \epsilon) \end{cases} \\
 \text{let } \overline{x : \tau} = \bar{e}_1 \overline{t : \kappa} = \bar{\tau} \text{ in } e_2 &\stackrel{\text{def}}{=} (\lambda \overline{x : \tau}. \Lambda \overline{t : \kappa}. e_2) \bar{e}_1 \bar{\tau} \\
 \exists \overline{t : \kappa}. \tau &\stackrel{\text{def}}{=} \begin{cases} \exists t : \kappa. \exists \overline{t' : \kappa'}. \tau & (\overline{t : \kappa} = t : \kappa \overline{t' : \kappa'}) \\ \tau & (\overline{t : \kappa} = \epsilon) \end{cases} \\
 \text{pack}\langle \bar{\tau}, e \rangle_{\exists \overline{t : \kappa}. \tau_0} &\stackrel{\text{def}}{=} \begin{cases} \text{pack}\langle \tau, \text{pack}\langle \bar{\tau}', e \rangle_{\exists \overline{t' : \kappa'}. \tau_0} \rangle_{\exists \overline{t : \kappa}. \tau_0} & (\bar{\tau} = \tau \bar{\tau}', \overline{t : \kappa} = t : \kappa \overline{t' : \kappa'}) \\ e & (\bar{\tau} = \epsilon, \overline{t : \kappa} = \epsilon) \end{cases} \\
 (\text{unpack}\langle \overline{t : \kappa}, x : \tau \rangle = e_1 \text{ in } e_2) &\stackrel{\text{def}}{=} \begin{cases} \text{unpack}\langle t : \kappa, x_1 : \exists \overline{t' : \kappa'}. \tau \rangle = e_1 \text{ in } & (\overline{t : \kappa} = t : \kappa \overline{t' : \kappa'}) \\ \text{unpack}\langle \overline{t' : \kappa'}, x_2 : \tau \rangle = x_1 \text{ in } e_2 & \\ \text{let } x : \tau = e_1 \text{ in } e_2 & (\overline{t : \kappa} = \epsilon) \end{cases}
 \end{aligned}$$

Kinding:

$$\boxed{\Gamma \vdash \tau : \kappa}$$

$$\begin{array}{c}
 \frac{\Gamma(t) = \kappa}{\Gamma \vdash t : \kappa} \quad \frac{\Gamma \vdash \tau_1 : \Omega \quad \Gamma \vdash \tau_2 : \Omega}{\Gamma \vdash \tau_1 \rightarrow \tau_2 : \Omega} \quad \frac{\bigwedge_l \Gamma \vdash \tau_l : \Omega}{\Gamma \vdash \{\bar{l} : \tau_l\} : \Omega} \\
 \frac{\Gamma, t : \kappa \vdash \tau : \Omega}{\Gamma \vdash \forall t : \kappa. \tau : \Omega} \quad \frac{\Gamma, t : \kappa \vdash \tau : \Omega}{\Gamma \vdash \exists t : \kappa. \tau : \Omega} \quad \frac{\Gamma, t : \kappa_1 \vdash \tau : \kappa_2}{\Gamma \vdash \lambda t : \kappa_1. \tau : \kappa_1 \rightarrow \kappa_2} \quad \frac{\Gamma \vdash \tau_1 : \kappa_2 \rightarrow \kappa \quad \Gamma \vdash \tau_2 : \kappa_2}{\Gamma \vdash \tau_1 \tau_2 : \kappa}
 \end{array}$$

Type equivalence:

$$\boxed{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}$$

$$\frac{\Gamma, t : \kappa_2 \vdash \tau_1 : \kappa \quad \Gamma \vdash \tau_2 : \kappa_2}{\Gamma \vdash (\lambda t : \kappa_2. \tau_1) \tau_2 \equiv \tau_1[t \leftarrow \tau_2] : \kappa} \quad \frac{t \notin \text{tyfv}(\tau) \quad \Gamma \vdash \tau : \kappa_1 \rightarrow \kappa_2}{\Gamma \vdash (\lambda t : \kappa_1. \tau t) \equiv \tau : \kappa_1 \rightarrow \kappa_2}$$

$$\frac{\tau_1 \equiv_{\alpha} \tau_2 \quad \Gamma \vdash \tau_1 : \kappa \quad \Gamma \vdash \tau_2 : \kappa}{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa} \quad \frac{\Gamma \vdash \tau_2 \equiv \tau_1 : \kappa}{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa} \quad \frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa \quad \Gamma \vdash \tau_2 \equiv \tau_3 : \kappa}{\Gamma \vdash \tau_1 \equiv \tau_3 : \kappa}$$

$$\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \Omega \quad \Gamma \vdash \tau'_1 \equiv \tau'_2 : \Omega}{\Gamma \vdash \tau_1 \rightarrow \tau'_1 \equiv \tau_2 \rightarrow \tau'_2 : \Omega} \quad \frac{\Gamma, t : \kappa \vdash \tau_1 \equiv \tau_2 : \Omega}{\Gamma \vdash \forall t : \kappa. \tau_1 \equiv \forall t : \kappa. \tau_2 : \Omega}$$

$$\frac{\Gamma, t : \kappa \vdash \tau_1 \equiv \tau_2 : \kappa'}{\Gamma \vdash \lambda t : \kappa. \tau_1 \equiv \lambda t : \kappa. \tau_2 : \kappa \rightarrow \kappa'} \quad \frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa' \rightarrow \kappa \quad \Gamma \vdash \tau'_1 \equiv \tau'_2 : \kappa'}{\Gamma \vdash \tau_1 \tau'_1 \equiv \tau_2 \tau'_2 : \kappa}$$

Typing:

$$\boxed{\Gamma \vdash e : \tau}$$

$$\frac{\Gamma \vdash \tau : \Omega \quad \Gamma(x) = \tau}{\Gamma \vdash x : \tau} \quad \frac{\Gamma \vdash \tau \equiv \tau' : \Omega \quad \Gamma \vdash e : \tau'}{\Gamma \vdash e : \tau}$$

$$\frac{\Gamma \vdash \tau_1 : \Omega \quad \Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2} \quad \frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau}$$

$$\frac{\bigwedge_l \Gamma \vdash e_l : \tau_l}{\Gamma \vdash \{\overline{l = e_l}\} : \{\overline{l = \tau_l}\}} \quad \frac{\Gamma \vdash e : \{\overline{l' = \tau_{l'}}\}}{\Gamma \vdash e.l : \tau_l}$$

$$\frac{\Gamma, t : \kappa \vdash e : \tau}{\Gamma \vdash \Lambda t : \kappa. e : (\forall t : \kappa. \tau)} \quad \frac{\Gamma \vdash e : (\forall t : \kappa. \tau_1) \quad \Gamma \vdash \tau_2 : \kappa}{\Gamma \vdash e \tau_2 : \tau_1[t \leftarrow \tau_2]}$$

$$\frac{\Gamma, t : \kappa \vdash \tau : \Omega \quad \Gamma \vdash \tau_t : \kappa \quad \Gamma \vdash e : \tau[t \leftarrow \tau_t]}{\Gamma \vdash \text{pack}\langle \tau_t, e \rangle_{\exists t : \kappa. \tau} : (\exists t : \kappa. \tau)} \quad \frac{\Gamma \vdash e_1 : (\exists t : \kappa. \tau_1) \quad \Gamma, t : \kappa, x : \tau_1 \vdash e_2 : \tau}{\Gamma \vdash \text{unpack}\langle t : \kappa, x : \tau_1 \rangle = e_1 \text{ in } e_2 : \tau}$$

Reduction:

$$\begin{aligned} v &::= \lambda x : \tau. e \mid \{\overline{l = e}\} \mid \Lambda t : \kappa. e \mid \text{pack}\langle \tau_t, e \rangle_{\exists t : \kappa. \tau} \\ C &::= [] \mid C e \mid v C \mid \{\overline{l = v}, l = C, l = e\} \mid C.l \mid C \tau \mid \text{pack}\langle \tau, C \rangle_{\tau} \mid \text{unpack}\langle t : \kappa, x : \tau \rangle = C \text{ in } e \end{aligned}$$

$$\boxed{e \Rightarrow e'}$$

$$\frac{}{(\lambda x : \tau. e)v \Rightarrow e[x \leftarrow v]} \quad \frac{}{\{\overline{l' = v_{l'}}\}.l \Rightarrow v_l} \quad \frac{}{(\Lambda t : \kappa. e)\tau \Rightarrow e[t \leftarrow \tau]}$$

$$\frac{}{\text{unpack}\langle t : \kappa, x : \tau \rangle = \text{pack}\langle \tau_t, v \rangle_{\tau_{\exists}} \text{ in } e \Rightarrow e[t \leftarrow \tau_t][x \leftarrow v]} \quad \frac{e \Rightarrow e'}{C[e] \Rightarrow C[e']}$$

Equivalence:

$$\boxed{\Gamma \vdash e_1 \equiv e_2 : \tau}$$

$$\frac{\Gamma, x : \tau_2 \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash (\lambda x : \tau_2. e_1) e_2 \equiv e_1[x \leftarrow e_2] : \tau} \quad \frac{x \notin \text{fv}(e) \quad \Gamma \vdash e : \tau_1 \rightarrow \tau_2}{\Gamma \vdash (\lambda x : \tau_1. e x) \equiv e : \tau_1 \rightarrow \tau_2}$$

$$\frac{\bigwedge_{l'} \Gamma \vdash e_{l'} : \tau_{l'}}{\Gamma \vdash \{\overline{l' = e_{l'}}\}.l \equiv e_l : \tau_l} \quad \frac{\Gamma \vdash e : \{\overline{l : \tau_l}\}}{\Gamma \vdash \{\overline{l = e.l}\} \equiv e : \{\overline{l : \tau_l}\}}$$

$$\frac{\Gamma, t : \kappa \vdash e : \tau}{\Gamma \vdash (\Lambda t : \kappa. e) \tau_2 \equiv e[t \leftarrow \tau_2] : \tau[t \leftarrow \tau_2]} \quad \frac{t \notin \text{tyfv}(e) \quad \Gamma \vdash e : \forall t : \kappa. \tau}{\Gamma \vdash (\Lambda t : \kappa. e t) \equiv e : \forall t : \kappa. \tau}$$

$$\frac{\Gamma, t : \kappa \vdash \tau_1 \equiv \tau'_1 : \Omega \quad \Gamma \vdash \tau_t : \kappa \quad \Gamma \vdash e_1 : \tau_1[t \leftarrow \tau_t] \quad \Gamma, t : \kappa, x : \tau_1 \vdash e_2 : \tau}{\Gamma \vdash \text{unpack}\langle t : \kappa, x : \tau'_1 \rangle = \text{pack}\langle \tau_t, e_1 \rangle_{\exists t : \kappa. \tau_1} \text{ in } e_2 \equiv e_2[t \leftarrow \tau_t][x \leftarrow e_1] : \tau}$$

$$\frac{\Gamma \vdash e : \exists t : \kappa. \tau \quad \Gamma, t : \kappa \vdash \tau \equiv \tau' : \Omega}{\Gamma \vdash \text{unpack}\langle t : \kappa, x : \tau' \rangle = e \text{ in } \text{pack}\langle t, x \rangle_{\exists t : \kappa. \tau} \equiv e : (\exists t : \kappa. \tau)}$$

$$\begin{array}{c}
\frac{e_1 \equiv_{\alpha} e_2 \quad \Gamma \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \quad \frac{\Gamma \vdash \tau \equiv \tau' : \Omega \quad \Gamma \vdash e_1 \equiv e_2 : \tau'}{\Gamma \vdash e_1 \equiv e_2 : \tau} \\
\frac{\Gamma \vdash e_2 \equiv e_1 : \tau}{\Gamma \vdash e_1 \equiv e_2 : \tau} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau \quad \Gamma \vdash e_2 \equiv e_3 : \tau}{\Gamma \vdash e_1 \equiv e_3 : \tau} \\
\frac{\Gamma, x : \tau \vdash e_1 \equiv e_2 : \tau'}{\Gamma \vdash \lambda x : \tau. e_1 \equiv \lambda x : \tau. e_2 : \tau \rightarrow \tau'} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau' \rightarrow \tau \quad \Gamma \vdash e'_1 \equiv e'_2 : \tau'}{\Gamma \vdash e_1 e'_1 \equiv e_2 e'_2 : \tau} \\
\frac{\bigwedge_l \Gamma \vdash e_{l,1} \equiv e_{l,2} : \tau_l}{\Gamma \vdash \{l = e_{l,1}\} \equiv \{l = e_{l,2}\} : \{\overline{l} : \tau_l\}} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \{l : \tau_l, \overline{l'} : \tau'\}}{\Gamma \vdash e_1.l \equiv e_2.l : \tau_l} \\
\frac{\Gamma, t : \kappa \vdash e_1 \equiv e_2 : \tau}{\Gamma \vdash \Lambda t : \kappa. e_1 \equiv \Lambda t : \kappa. e_2 : (\forall t : \kappa. \tau)} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \forall t : \kappa. \tau \quad \Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}{\Gamma \vdash e_1 \tau_1 \equiv e_2 \tau_2 : \tau[t \leftarrow \tau_1]} \\
\frac{\Gamma \vdash \tau'_1 \equiv \tau'_2 : \kappa \quad \Gamma \vdash e_1 \equiv e_2 : \tau_1[t \leftarrow \tau'_1] \quad \Gamma, t : \kappa. \tau_1 \equiv \tau_2 : \Omega}{\Gamma \vdash \text{pack}\langle \tau'_1, e_1 \rangle_{\exists t : \kappa. \tau_1} \equiv \text{pack}\langle \tau'_2, e_2 \rangle_{\exists t : \kappa. \tau_2} : (\exists t : \kappa. \tau_1)} \\
\frac{\Gamma, t : \kappa \vdash \tau'_1 \equiv \tau'_2 : \Omega \quad \Gamma \vdash e'_1 \equiv e'_2 : (\exists t : \kappa. \tau'_1) \quad \Gamma, t : \kappa, x : \tau'_1 \vdash e_1 \equiv e_2 : \tau}{\Gamma \vdash \text{unpack}\langle t : \kappa, x : \tau'_1 \rangle = e'_1 \text{ in } e_1 \equiv \text{unpack}\langle t : \kappa, x : \tau'_2 \rangle = e'_2 \text{ in } e_2 : \tau}
\end{array}$$

4.1.2 Syntax

| | |
|--------------------------------|-----------------------------|
| $X ::= \dots$ | (identifier) |
| $K ::= \dots$ | (kind) |
| $T ::= \dots \mid P$ | (type) |
| $E ::= \dots \mid P$ | (expression) |
| $P ::= M$ | (path) |
| $M ::= X$ | (identifier) |
| $\mid \{B\}$ | (bindings) |
| $\mid M.X$ | (projection) |
| $B ::= \text{val } X = E$ | (value binding) |
| $\mid \text{type } X = T$ | (type binding) |
| $\mid \text{module } X = M$ | (module binding) |
| $\mid \text{signature } X = S$ | (signature binding) |
| $\mid \text{include } M$ | (module including) |
| $\mid \epsilon$ | (empty binding) |
| $\mid B; B$ | (binding concatenation) |
| $S ::= P$ | (signature path) |
| $\mid \{D\}$ | (declarations) |
| $D ::= \text{val } X : T$ | (value declaration) |
| $\mid \text{type } X = T$ | (type binding) |
| $\mid \text{module } X : S$ | (module declaration) |
| $\mid \text{signature } X = S$ | (signature binding) |
| $\mid \text{include } S$ | (signature including) |
| $\mid \epsilon$ | (empty declaration) |
| $\mid D; D$ | (declaration concatenation) |

4.1.3 Signature

| | |
|------------------------------------|-----------------------------------|
| $\Sigma ::= [\tau]$ | (anonymous value declaration) |
| $\mid [= \tau : \kappa]$ | (anonymous type declaration) |
| $\mid [= \Sigma]$ | (anonymous signature declaration) |
| $\mid \{\overline{l_X} : \Sigma\}$ | (structural signature) |

Atomic Signature:

$$[\tau] \stackrel{\text{def}}{=} \{\text{val} : \tau\}$$

$$\begin{aligned}
[e] &\stackrel{\text{def}}{=} \{\text{val} = e\} \\
[= \tau : \kappa] &\stackrel{\text{def}}{=} \{\text{type} : \forall t : (\kappa \rightarrow \Omega). t \tau \rightarrow t \tau\} \\
[\tau : \kappa] &\stackrel{\text{def}}{=} \{\text{type} = \Lambda t : (\kappa \rightarrow \Omega). \lambda x : (t \tau). x\} \\
[= \Sigma] &\stackrel{\text{def}}{=} \{\text{sig} : \Sigma \rightarrow \Sigma\} \\
[\Sigma] &\stackrel{\text{def}}{=} \{\text{sig} = \lambda x : \Sigma. x\}
\end{aligned}$$

NotAtomic(Σ)

$$\overline{\text{NotAtomic}(\{l_X : \Sigma\})}$$

Admissible kinding:

$\Gamma \vdash \tau : \kappa$

$$\begin{aligned}
&\frac{\Gamma \vdash \tau : \Omega}{\Gamma \vdash [\tau] : \Omega} \text{ K-A-Val} \\
&\frac{\Gamma \vdash \tau : \kappa}{\Gamma \vdash [= \tau : \kappa] : \Omega} \text{ K-A-Typ} \\
&\frac{\Gamma \vdash \Sigma : \Omega}{\Gamma \vdash [= \Sigma] : \Omega} \text{ K-A-Sig}
\end{aligned}$$

Admissible type equivalence:

$\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa$

$$\begin{aligned}
&\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \Omega}{\Gamma \vdash [\tau_1] \equiv [\tau_2] : \Omega} \text{ T-Eq-Cong-A-Val} \\
&\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}{\Gamma \vdash [= \tau_1 : \kappa] \equiv [= \tau_2 : \kappa] : \Omega} \text{ T-Eq-Cong-A-Typ} \\
&\frac{\Gamma \vdash \Sigma_1 \equiv \Sigma_2 : \Omega}{\Gamma \vdash [= \Sigma_1] \equiv [= \Sigma_2] : \Omega} \text{ T-Eq-Cong-A-Sig}
\end{aligned}$$

Admissible typing:

$\Gamma \vdash e : \tau$

$$\begin{aligned}
&\frac{\Gamma \vdash e : \tau}{\Gamma \vdash [e] : [\tau]} \text{ T-A-Val} \\
&\frac{\Gamma \vdash \tau : \kappa}{\Gamma \vdash [\tau : \kappa] : [= \tau : \kappa]} \text{ T-A-Typ} \\
&\frac{\Gamma \vdash \Sigma : \Omega}{\Gamma \vdash [\Sigma] : [= \Sigma]} \text{ T-A-Sig}
\end{aligned}$$

Admissible equivalence:

$\Gamma \vdash e_1 \equiv e_2 : \tau$

$$\begin{aligned}
&\frac{\Gamma \vdash e : \tau}{\Gamma \vdash [e].\text{val} \equiv e : \tau} \text{ Eq-}\beta\text{-A-Val} \quad \frac{\Gamma \vdash e : [\tau]}{\Gamma \vdash [e.\text{val}] \equiv e : [\tau]} \text{ Eq-}\eta\text{-A-Val} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau}{\Gamma \vdash [e_1] \equiv [e_2] : [\tau]} \text{ Eq-Cong-A-Val} \\
&\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}{\Gamma \vdash [\tau_1 : \kappa] \equiv [\tau_2 : \kappa] : [= \tau_1 : \kappa]} \text{ Eq-Cong-A-Typ} \\
&\frac{\Gamma \vdash \Sigma_1 \equiv \Sigma_2 : \Omega}{\Gamma \vdash [\Sigma_1] \equiv [\Sigma_2] : [= \Sigma_1]} \text{ Eq-Cong-A-Sig}
\end{aligned}$$

4.1.4 Elaboration

Signature:

$$\boxed{\Gamma \vdash S \rightsquigarrow \Sigma}$$

$$\frac{\Gamma \vdash P : [= \Sigma] \rightsquigarrow e}{\Gamma \vdash P \rightsquigarrow \Sigma} \text{ S-Path}$$

$$\frac{\Gamma \vdash D \rightsquigarrow \Sigma}{\Gamma \vdash \{D\} \rightsquigarrow \Sigma} \text{ S-Struct}$$

Declarations:

$$\boxed{\Gamma \vdash D \rightsquigarrow \Sigma}$$

$$\frac{\Gamma \vdash T : \Omega \rightsquigarrow \tau}{\Gamma \vdash \text{val } X : T \rightsquigarrow \{l_X : [\tau]\}} \text{ D-Val}$$

$$\frac{\Gamma \vdash T : \kappa \rightsquigarrow \tau}{\Gamma \vdash \text{type } X = T \rightsquigarrow \{l_X : [= \tau : \kappa]\}} \text{ D-Typ-Eq}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Sigma}{\Gamma \vdash \text{module } X : S \rightsquigarrow \{l_X : \Sigma\}} \text{ D-Mod}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Sigma}{\Gamma \vdash \text{signature } X = S \rightsquigarrow \{l_X : [= \Sigma]\}} \text{ D-Sig-Eq}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \{\overline{l_X : \Sigma}\}}{\Gamma \vdash \text{include } S \rightsquigarrow \{\overline{l_X : \Sigma}\}} \text{ D-Incl}$$

$$\frac{\Gamma \vdash \epsilon \rightsquigarrow \{\}}{\Gamma \vdash \epsilon \rightsquigarrow \{\}} \text{ D-Emt}$$

$$\frac{\{\overline{l_{X_1}}\} \cap \{\overline{l_{X_2}}\} = \emptyset \quad \Gamma \vdash D_1 \rightsquigarrow \{\overline{l_{X_1} : \Sigma_1}\} \quad \Gamma, \overline{x_{X_1} : \Sigma_1} \vdash D_2 \rightsquigarrow \{\overline{l_{X_2} : \Sigma_2}\}}{\Gamma \vdash D_1; D_2 \rightsquigarrow \{\overline{l_{X_1} : \Sigma_1}, \overline{l_{X_2} : \Sigma_2}\}} \text{ D-Seq}$$

Module:

$$\boxed{\Gamma \vdash M : \Sigma \rightsquigarrow e}$$

$$\frac{\Gamma(x_X) = \Sigma}{\Gamma \vdash X : \Sigma \rightsquigarrow x_X} \text{ M-Var}$$

$$\frac{\Gamma \vdash B : \Sigma \rightsquigarrow e}{\Gamma \vdash \{B\} : \Sigma \rightsquigarrow e} \text{ M-Struct}$$

$$\frac{\Gamma \vdash M : \{l_X : \Sigma, \overline{l_{X'} : \Sigma'}\} \rightsquigarrow e}{\Gamma \vdash M.X : \Sigma \rightsquigarrow e.l_X} \text{ M-Dot}$$

Bindings:

$$\boxed{\Gamma \vdash B : \Sigma \rightsquigarrow e}$$

$$\frac{\Gamma \vdash E : \tau \rightsquigarrow e}{\Gamma \vdash \text{val } X = E : \{l_X : [\tau]\} \rightsquigarrow \{l_X = [e]\}} \text{ B-Val}$$

$$\frac{\Gamma \vdash T : \kappa \rightsquigarrow \tau}{\Gamma \vdash \text{type } X = T : \{l_X : [= \tau : \kappa]\} \rightsquigarrow \{l_X = [\tau : \kappa]\}} \text{ B-Typ}$$

$$\frac{\Gamma \vdash M : \Sigma \rightsquigarrow e \quad \text{NotAtomic}(\Sigma)}{\Gamma \vdash \text{module } X = M : \{l_X : \Sigma\} \rightsquigarrow \{l_X = e\}} \text{ B-Mod}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Sigma}{\Gamma \vdash \text{signature } X = S : \{l_X : [= \Sigma]\} \rightsquigarrow \{l_X = [\Sigma]\}} \text{ B-Sig}$$

$$\frac{\Gamma \vdash M : \{\overline{l_X : \Sigma}\} \rightsquigarrow e}{\Gamma \vdash \text{include } M : \{\overline{l_X : \Sigma}\} \rightsquigarrow e} \text{ B-Incl}$$

$$\begin{array}{c}
\overline{\Gamma \vdash \epsilon : \{\} \rightsquigarrow \{\}} \quad \text{B-Emt} \\
\frac{\overline{l'_{X_1} = \overline{l_{X_1}} \setminus \overline{l_{X_2}}} \quad \overline{l'_{X_1} : \Sigma'_1 \subseteq \overline{l_{X_1} : \Sigma_1}} \quad \overline{\Gamma \vdash B_1 : \{\overline{l_{X_1} : \Sigma_1}\} \rightsquigarrow e_1}}{\Sigma = \{\overline{l'_{X_1} : \Sigma'_1}, \overline{l_{X_2} : \Sigma_2}\} \quad \overline{\Gamma, x_{X_1} : \Sigma_1 \vdash B_2 : \{\overline{l_{X_2} : \Sigma_2}\} \rightsquigarrow e_2}} \quad \text{B-Seq} \\
\frac{\text{let } x_1 = e_1 \text{ in } \overline{\Gamma \vdash B_1; B_2 : \Sigma \rightsquigarrow}}{\text{let } x_2 = (\text{let } x_{X_1} : \Sigma_1 = x_1.l_{X_1} \text{ in } e_2) \text{ in } \overline{\{l'_{X_1} = x_1.l'_{X_1}, l_{X_2} = x_2.l_{X_2}\}}}
\end{array}$$

Path:

$$\boxed{\Gamma \vdash P : \Sigma \rightsquigarrow e}$$

Use M-Dot.

$$\boxed{\Gamma \vdash T : \kappa \rightsquigarrow \tau}$$

$$\frac{\Gamma \vdash P : [= \tau : \kappa] \rightsquigarrow e}{\Gamma \vdash P : \kappa \rightsquigarrow \tau} \quad \text{T-Elab-Path}$$

$$\boxed{\Gamma \vdash E : \tau \rightsquigarrow e}$$

$$\frac{\Gamma \vdash P : [\tau] \rightsquigarrow e}{\Gamma \vdash P : \tau \rightsquigarrow e.\text{val}} \quad \text{E-Path}$$

4.2 F-ing modules

[RRD14]

4.2.1 Internal Language

See 第 4.1.1 小節.

4.2.2 Syntax

| | | | |
|-----|-------|--|----------------------------------|
| X | $::=$ | \dots | (identifier) |
| K | $::=$ | \dots | (kind) |
| T | $::=$ | $\dots \mid P$ | (type) |
| E | $::=$ | $\dots \mid P$ | (expression) |
| P | $::=$ | M | (path) |
| M | $::=$ | X | (identifier) |
| | | $\mid \{B\}$ | (bindings) |
| | | $\mid M.X$ | (projection) |
| | | $\mid \text{fun } X : S \Rightarrow M$ | (functor) |
| | | $\mid X X$ | (functor application) |
| | | $\mid X :> S$ | (sealing) |
| B | $::=$ | $\text{val } X = E$ | (value binding) |
| | | $\mid \text{type } X = T$ | (type binding) |
| | | $\mid \text{module } X = M$ | (module binding) |
| | | $\mid \text{signature } X = S$ | (signature binding) |
| | | $\mid \text{include } M$ | (module including) |
| | | $\mid \epsilon$ | (empty binding) |
| | | $\mid B; B$ | (binding concatenation) |
| S | $::=$ | P | (signature path) |
| | | $\mid \{D\}$ | (declarations) |
| | | $\mid (X : S) \rightarrow S$ | ((generative) functor signature) |
| | | $\mid S \text{ where type } \bar{X} = T$ | (bounded signature) |
| D | $::=$ | $\text{val } X : T$ | (value declaration) |
| | | $\mid \text{type } X = T$ | (type binding) |
| | | $\mid \text{type } X : K$ | (type declaration) |
| | | $\mid \text{module } X : S$ | (module declaration) |
| | | $\mid \text{signature } X = S$ | (signature binding) |
| | | $\mid \text{include } S$ | (signature including) |
| | | $\mid \epsilon$ | (empty declaration) |
| | | $\mid D; D$ | (declaration concatenation) |

4.2.3 Signature

| | | | |
|----------|-------|---|--------------------------------|
| Ξ | $::=$ | $\overline{\exists t : \kappa. \Sigma}$ | (abstract signature) |
| Σ | $::=$ | $[\tau]$ | (atomic value declaration) |
| | | $\mid [= \tau : \kappa]$ | (atomic type declaration) |
| | | $\mid [= \Xi]$ | (atomic signature declaration) |
| | | $\mid \{\overline{l_X : \Sigma}\}$ | (structure signature) |
| | | $\mid \forall t : \kappa. \Sigma \rightarrow \Xi$ | (functor signature) |

Atomic Signature:

$$[\tau] \stackrel{\text{def}}{=} \{\text{val} : \tau\}$$

$$\begin{aligned}
[e] &\stackrel{\text{def}}{=} \{\text{val} = e\} \\
[= \tau : \kappa] &\stackrel{\text{def}}{=} \{\text{type} : \forall t : (\kappa \rightarrow \Omega). t \tau \rightarrow t \tau\} \\
[\tau : \kappa] &\stackrel{\text{def}}{=} \{\text{type} = \Lambda t : (\kappa \rightarrow \Omega). \lambda x : (t \tau). x\} \\
[= \Xi] &\stackrel{\text{def}}{=} \{\text{sig} : \Xi \rightarrow \Xi\} \\
[\Xi] &\stackrel{\text{def}}{=} \{\text{sig} = \lambda x : \Xi. x\}
\end{aligned}$$

$\text{NotAtomic}(\Sigma)$

$$\frac{}{\text{NotAtomic}(\{l_X : \Sigma\})} \quad \frac{}{\text{NotAtomic}(\forall t : \kappa. \Sigma \rightarrow \Xi)}$$

Admissible kinding:

$\Gamma \vdash \tau : \kappa$

$$\begin{aligned}
&\frac{\Gamma \vdash \tau : \Omega}{\Gamma \vdash [\tau] : \Omega} \text{ K-A-Val} \\
&\frac{\Gamma \vdash \tau : \kappa}{\Gamma \vdash [= \tau : \kappa] : \Omega} \text{ K-A-Typ} \\
&\frac{\Gamma \vdash \Xi : \Omega}{\Gamma \vdash [= \Xi] : \Omega} \text{ K-A-Sig}
\end{aligned}$$

Admissible type equivalence:

$\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa$

$$\begin{aligned}
&\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \Omega}{\Gamma \vdash [\tau_1] \equiv [\tau_2] : \Omega} \text{ T-Eq-Cong-A-Val} \\
&\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}{\Gamma \vdash [= \tau_1 : \kappa] \equiv [= \tau_2 : \kappa] : \Omega} \text{ T-Eq-Cong-A-Typ} \\
&\frac{\Gamma \vdash \Xi_1 \equiv \Xi_2 : \Omega}{\Gamma \vdash [= \Xi_1] \equiv [= \Xi_2] : \Omega} \text{ T-Eq-Cong-A-Sig}
\end{aligned}$$

Admissible typing:

$\Gamma \vdash e : \tau$

$$\begin{aligned}
&\frac{\Gamma \vdash e : \tau}{\Gamma \vdash [e] : [\tau]} \text{ T-A-Val} \\
&\frac{\Gamma \vdash \tau : \kappa}{\Gamma \vdash [\tau : \kappa] : [= \tau : \kappa]} \text{ T-A-Typ} \\
&\frac{\Gamma \vdash \Xi : \Omega}{\Gamma \vdash [\Xi] : [= \Xi]} \text{ T-A-Sig}
\end{aligned}$$

Admissible equivalence:

$\Gamma \vdash e_1 \equiv e_2 : \tau$

$$\begin{aligned}
&\frac{\Gamma \vdash e : \tau}{\Gamma \vdash [e]. \text{val} \equiv e : \tau} \text{ Eq-}\beta\text{-A-Val} \quad \frac{\Gamma \vdash e : [\tau]}{\Gamma \vdash [e. \text{val}] \equiv e : [\tau]} \text{ Eq-}\eta\text{-A-Val} \quad \frac{\Gamma \vdash e_1 \equiv e_2 : \tau}{\Gamma \vdash [e_1] \equiv [e_2] : [\tau]} \text{ Eq-Cong-A-Val} \\
&\frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \kappa}{\Gamma \vdash [\tau_1 : \kappa] \equiv [\tau_2 : \kappa] : [= \tau_1 : \kappa]} \text{ Eq-Cong-A-Typ} \\
&\frac{\Gamma \vdash \Xi_1 \equiv \Xi_2 : \Omega}{\Gamma \vdash [\Xi_1] \equiv [\Xi_2] : [= \Xi_1]} \text{ Eq-Cong-A-Sig}
\end{aligned}$$

4.2.4 (Generative) Elaboration

Signature:

$$\boxed{\Gamma \vdash S \rightsquigarrow \Xi}$$

$$\begin{array}{c} \frac{\Gamma \vdash P : [= \Xi] \rightsquigarrow e}{\Gamma \vdash P \rightsquigarrow \Xi} \text{ S-Path} \\ \frac{\Gamma \vdash D \rightsquigarrow \Xi}{\Gamma \vdash \{D\} \rightsquigarrow \Xi} \text{ S-Struct} \\ \frac{\Gamma \vdash S_1 \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \Sigma \quad \Gamma, \overline{t} : \overline{\kappa}, x_X : \Sigma \vdash S_2 \rightsquigarrow \Xi}{\Gamma \vdash (X : S_1) \rightarrow S_2 \rightsquigarrow \forall \overline{t} : \overline{\kappa}. \Sigma \rightarrow \Xi} \text{ S-Funct} \\ \frac{\Gamma \vdash S \rightsquigarrow \exists \overline{t}_1 : \overline{\kappa}_1 \overline{t} : \overline{\kappa}_2 \overline{\kappa}_2. \Sigma \quad \Sigma. \overline{l}_X = [= \overline{t} : \overline{\kappa}] \quad \Gamma \vdash T : \overline{\kappa} \rightsquigarrow \tau}{\Gamma \vdash S \text{ where type } \overline{X} = T \rightsquigarrow \exists \overline{t}_1 : \overline{\kappa}_1 \overline{t}_2 : \overline{\kappa}_2. \Sigma [\overline{t} \leftarrow \tau]} \text{ S-Where-Typ} \end{array}$$

Declarations:

$$\boxed{\Gamma \vdash D \rightsquigarrow \Xi}$$

$$\begin{array}{c} \frac{\Gamma \vdash T : \Omega \rightsquigarrow \tau}{\Gamma \vdash \text{val } X : T \rightsquigarrow \{l_X : [\tau]\}} \text{ D-Val} \\ \frac{\Gamma \vdash T : \overline{\kappa} \rightsquigarrow \tau}{\Gamma \vdash \text{type } X = T \rightsquigarrow \{l_X : [= \tau : \overline{\kappa}]\}} \text{ D-Typ-Eq} \\ \frac{\Gamma \vdash K \rightsquigarrow \overline{\kappa}}{\Gamma \vdash \text{type } X : K \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \{l_X : [= \overline{t} : \overline{\kappa}]\}} \text{ D-Typ} \\ \frac{\Gamma \vdash S \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \Sigma}{\Gamma \vdash \text{module } X : S \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \{l_X : \Sigma\}} \text{ D-Mod} \\ \frac{\Gamma \vdash S \rightsquigarrow \Xi}{\Gamma \vdash \text{signature } X = S \rightsquigarrow \{l_X : [= \Xi]\}} \text{ D-Sig-Eq} \\ \frac{\Gamma \vdash S \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \{\overline{l}_X : \Sigma\}}{\Gamma \vdash \text{include } S \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \{\overline{l}_X : \Sigma\}} \text{ D-Incl} \\ \frac{}{\Gamma \vdash \epsilon \rightsquigarrow \{\}} \text{ D-Emt} \\ \frac{\{\overline{l}_{X_1}\} \cap \{\overline{l}_{X_2}\} = \emptyset \quad \Gamma \vdash D_1 \rightsquigarrow \exists \overline{t}_1 : \overline{\kappa}_1. \{\overline{l}_{X_1} : \Sigma_1\} \quad \Gamma, \overline{t}_1 : \overline{\kappa}_1, x_{X_1} : \Sigma_1 \vdash D_2 \rightsquigarrow \exists \overline{t}_2 : \overline{\kappa}_2. \{\overline{l}_{X_2} : \Sigma_2\}}{\Gamma \vdash D_1; D_2 \rightsquigarrow \exists \overline{t}_1 : \overline{\kappa}_1 \overline{t}_2 : \overline{\kappa}_2. \{\overline{l}_{X_1} : \Sigma_1 \overline{l}_{X_2} : \Sigma_2\}} \text{ D-Seq} \end{array}$$

Matching:

$$\boxed{\Gamma \vdash \Sigma_1 \leq \exists \overline{t} : \overline{\kappa}. \Sigma_2 \uparrow \overline{\tau} \rightsquigarrow e}$$

$$\frac{\Gamma \vdash \Sigma_1 \leq \Sigma_2 [\overline{t} \leftarrow \overline{\tau}_t] \rightsquigarrow e \quad \bigwedge_t \Gamma \vdash \tau_t : \overline{\kappa}_t}{\Gamma \vdash \Sigma_1 \leq \exists \overline{t} : \overline{\kappa}_t. \Sigma_2 \uparrow \overline{\tau}_t \rightsquigarrow e} \text{ U-Match}$$

Subtyping:

$$\boxed{\Gamma \vdash \Xi_1 \leq \Xi_2 \rightsquigarrow e}$$

$$\begin{array}{c} \frac{\Gamma \vdash \tau_1 \leq \tau_2 \rightsquigarrow e}{\Gamma \vdash [\tau_1] \leq [\tau_2] \rightsquigarrow \lambda x : [\tau_1]. [e (x. \text{val})]} \text{ U-Val} \\ \frac{\Gamma \vdash \tau_1 \equiv \tau_2 : \overline{\kappa}}{\Gamma \vdash [= \tau_1 : \overline{\kappa}] \leq [= \tau_2 : \overline{\kappa}] \rightsquigarrow \lambda x : [= \tau_1 : \overline{\kappa}]. x} \text{ U-Typ} \\ \frac{\Gamma \vdash \Xi_1 \leq \Xi_2 \rightsquigarrow e_1 \quad \Gamma \vdash \Xi_2 \leq \Xi_1 \rightsquigarrow e_2}{\Gamma \vdash [= \Xi_1] \leq [= \Xi_2] \rightsquigarrow \lambda x : [= \Xi_1]. [\Xi_2]} \text{ U-Sig} \end{array}$$

$$\begin{array}{c}
\frac{\bigwedge_l \Gamma \vdash \Sigma_{l_1} \leq \Sigma_{l_2} \rightsquigarrow e_l}{\Gamma \vdash \{\overline{l} : \Sigma_{l_1}, \overline{l'} : \Sigma'\} \leq \{\overline{l} : \Sigma_{l_2}\} \rightsquigarrow \lambda x : \{\overline{l} : \Sigma_{l_1}, \overline{l'} : \Sigma'\}. \{\overline{l} = e_l(x.l)\}} \text{U-Struct} \\
\frac{\Gamma, \overline{t_2} : \overline{\kappa_2} \vdash \Sigma_2 \leq \exists \overline{t_1} : \overline{\kappa_1}. \Sigma_1 \uparrow \overline{\tau} \rightsquigarrow e_1 \quad \Gamma, \overline{t_2} : \overline{\kappa_2} \vdash \Xi_1[\overline{t_1} \leftarrow \overline{\tau}] \leq \Xi_2 \rightsquigarrow e_2}{\Gamma \vdash \forall \overline{t_1} : \overline{\kappa_1}. \Sigma_1 \rightarrow \Xi_1 \leq \forall \overline{t_2} : \overline{\kappa_2}. \Sigma_2 \rightarrow \Xi_2 \rightsquigarrow \lambda x_1 : (\forall \overline{t_1} : \overline{\kappa_1}. \Sigma_1 \rightarrow \Xi_1). \lambda x_2 : \Sigma_2. e_2(x_1 \overline{\tau}(e_1 x_2))} \text{U-Funct} \\
\frac{\Gamma, \overline{t_1} : \overline{\kappa_1} \vdash \Sigma_1 \leq \exists \overline{t_2} : \overline{\kappa_2}. \Sigma_2 \uparrow \overline{\tau} \rightsquigarrow e}{\Gamma \vdash \exists \overline{t_1} : \overline{\kappa_1}. \Sigma_1 \leq \exists \overline{t_2} : \overline{\kappa_2}. \Sigma_2 \rightsquigarrow \lambda x_1 : (\exists \overline{t_1} : \overline{\kappa_1}. \Sigma_1). \text{unpack}(\overline{t_1} : \overline{\kappa_1}, x'_1 : \Sigma_1) = x_1 \text{ in pack}(\overline{\tau}, e x'_1)_{\exists \overline{t_2} : \overline{\kappa_2}. \Sigma_2}} \text{U-Abs}
\end{array}$$

Module:

$$\boxed{\Gamma \vdash M : \Xi \rightsquigarrow e}$$

$$\begin{array}{c}
\frac{\Gamma(x_X) = \Sigma}{\Gamma \vdash X : \Sigma \rightsquigarrow x_X} \text{M-Var} \\
\frac{\Gamma \vdash B : \Xi \rightsquigarrow e}{\Gamma \vdash \{B\} : \Xi \rightsquigarrow e} \text{M-Struct} \\
\frac{\Gamma \vdash M : \exists \overline{t} : \overline{\kappa}. \{\overline{l_X} : \Sigma, \overline{l_{X'}} : \Sigma'\} \rightsquigarrow e}{\Gamma \vdash M.X : \exists \overline{t} : \overline{\kappa}. \Sigma \rightsquigarrow \text{unpack}(\overline{t} : \overline{\kappa}, x : \{\overline{l_X} : \Sigma, \overline{l_{X'}} : \Sigma'\}) = e \text{ in pack}(\overline{t}, x.l_X)_{\exists \overline{t} : \overline{\kappa}. \Sigma}} \text{M-Dot} \\
\frac{\Sigma \vdash S \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \Sigma \quad \Gamma, \overline{t} : \overline{\kappa}, x_X : \Sigma \vdash M : \Xi \rightsquigarrow e}{\Gamma \vdash \text{fun } X : S \Rightarrow M : \forall \overline{t} : \overline{\kappa}. \Sigma \rightarrow \Xi \rightsquigarrow \Lambda \overline{t} : \overline{\kappa}. \lambda x_X : \Sigma. e} \text{M-Funct} \\
\frac{\Gamma(x_{X_1}) = \forall \overline{t} : \overline{\kappa}. \Sigma' \rightarrow \Xi \quad \Gamma(x_{X_2}) = \Sigma \quad \Gamma \vdash \Sigma \leq \exists \overline{t} : \overline{\kappa}. \Sigma' \uparrow \overline{\tau} \rightsquigarrow e}{\Gamma \vdash X_1 X_2 : \Xi[\overline{t} \leftarrow \overline{\tau}] \rightsquigarrow x_{X_1} \overline{\tau}(e x_{X_2})} \text{M-App} \\
\frac{\Gamma(x_X) = \Sigma \quad \Gamma \vdash S \rightsquigarrow \exists \overline{t} : \overline{\kappa}. \Sigma' \quad \Gamma \vdash \Sigma \leq \exists \overline{t} : \overline{\kappa}. \Sigma' \uparrow \overline{\tau} \rightsquigarrow e}{\Gamma \vdash X :> S : \exists \overline{t} : \overline{\kappa}. \Sigma' \rightsquigarrow \text{pack}(\overline{\tau}, e x_X)_{\exists \overline{t} : \overline{\kappa}. \Sigma'}} \text{M-Seal}
\end{array}$$

Bindings:

$$\boxed{\Gamma \vdash B : \Xi \rightsquigarrow e}$$

$$\begin{array}{c}
\frac{\Gamma \vdash E : \tau \rightsquigarrow e}{\Gamma \vdash \text{val } X = E : \{\overline{l_X} : [\tau]\} \rightsquigarrow \{\overline{l_X} = [e]\}} \text{B-Val} \\
\frac{\Gamma \vdash T : \kappa \rightsquigarrow \tau}{\Gamma \vdash \text{type } X = T : \{\overline{l_X} : [= \tau : \kappa]\} \rightsquigarrow \{\overline{l_X} = [\tau : \kappa]\}} \text{B-Typ} \\
\frac{\Gamma \vdash M : \exists \overline{t} : \overline{\kappa}. \Sigma \rightsquigarrow e \quad \text{NotAtomic}(\Sigma)}{\Gamma \vdash \text{module } X = M : \exists \overline{t} : \overline{\kappa}. \{\overline{l_X} : \Sigma\} \rightsquigarrow \text{unpack}(\overline{t} : \overline{\kappa}, x : \Sigma) = e \text{ in pack}(\overline{t}, \{\overline{l_X} = x\})_{\exists \overline{t} : \overline{\kappa}. \{\overline{l_X} : \Sigma\}}} \text{B-Mod} \\
\frac{\Gamma \vdash S \rightsquigarrow \Xi}{\Gamma \vdash \text{signature } X = S : \{\overline{l_X} : [= \Xi]\} \rightsquigarrow \{\overline{l_X} = [\Xi]\}} \text{B-Sig} \\
\frac{\Gamma \vdash M : \exists \overline{t} : \overline{\kappa}. \{\overline{l_X} : \Sigma\} \rightsquigarrow e}{\Gamma \vdash \text{include } M : \exists \overline{t} : \overline{\kappa}. \{\overline{l_X} : \Sigma\} \rightsquigarrow e} \text{B-Incl} \\
\frac{}{\Gamma \vdash \epsilon : \{\} \rightsquigarrow \{\}} \text{B-Emt} \\
\frac{\overline{l'_{X_1}} = \overline{l_{X_1}} \setminus \overline{l_{X_2}} \quad \overline{l'_{X_1}} : \Sigma'_1 \subseteq \overline{l_{X_1}} : \Sigma_1 \quad \Gamma \vdash B_1 : \exists \overline{t_1} : \overline{\kappa_1}. \{\overline{l_{X_1}} : \Sigma_1\} \rightsquigarrow e_1 \quad \Sigma = \{\overline{l'_{X_1}} : \Sigma'_1, \overline{l_{X_2}} : \Sigma_2\} \quad \Gamma, \overline{t_1} : \overline{\kappa_1}, x_{X_1} : \Sigma_1 \vdash B_2 : \exists \overline{t_2} : \overline{\kappa_2}. \{\overline{l_{X_2}} : \Sigma_2\} \rightsquigarrow e_2}{\Gamma \vdash B_1; B_2 : \exists \overline{t_1} : \overline{\kappa_1} \overline{t_2} : \overline{\kappa_2}. \Sigma \rightsquigarrow \text{unpack}(\overline{t_1} : \overline{\kappa_1}, x_1) = e_1 \text{ in } \text{unpack}(\overline{t_2} : \overline{\kappa_2}, x_2) = (\text{let } x_{X_1} : \Sigma_1 = x_1.l_{X_1} \text{ in } e_2) \text{ in } \text{pack}(\overline{t_1} \overline{t_2}, \{\overline{l'_{X_1}} = x_1.l'_{X_1}, \overline{l_{X_2}} = x_2.l_{X_2}\})_{\exists \overline{t_1} : \overline{\kappa_1} \overline{t_2} : \overline{\kappa_2}. \Sigma}} \text{B-Seq}
\end{array}$$

Path:

$$\boxed{\Gamma \vdash P : \Sigma \rightsquigarrow e}$$

$$\frac{\Gamma \vdash P : \exists \overline{t} : \overline{\kappa}. \Sigma \quad \Gamma \vdash \Sigma : \Omega}{\Gamma \vdash P : \Sigma \rightsquigarrow \text{unpack}(\overline{t} : \overline{\kappa}, x) = e \text{ in } x} \text{P-Mod}$$

$$\boxed{\Gamma \vdash T : \kappa \rightsquigarrow \tau}$$

$$\frac{\Gamma \vdash P : [= \tau : \kappa] \rightsquigarrow e}{\Gamma \vdash P : \kappa \rightsquigarrow \tau} \text{ T-Elab-Path}$$

$$\boxed{\Gamma \vdash E : \tau \rightsquigarrow e}$$

$$\frac{\Gamma \vdash P : [\tau] \rightsquigarrow e}{\Gamma \vdash P : \tau \rightsquigarrow e.\text{val}} \text{ E-Path}$$

4.2.5 Modules as First-Class Values

$$\begin{aligned} T &::= \dots \mid \text{pack } S \\ E &::= \dots \mid \text{pack } M : S \\ M &::= \dots \mid \text{unpack } E : S \end{aligned}$$

Rootedness:

$$\boxed{t : \kappa \text{ rooted in } \Sigma \text{ at } \overline{l}_X}$$

$$\frac{t = \tau'}{t : \kappa \text{ rooted in } [= \tau : \kappa] \text{ at } \epsilon} \quad \frac{t : \kappa \text{ rooted in } \{\overline{l}_X : \Sigma\}.l \text{ at } \overline{l}'}{t : \kappa \text{ rooted in } \{\overline{l}_X : \Sigma\} \text{ at } l \overline{l}'}$$

Rooted ordering:

$$t_1 : \kappa_1 \leq_{\Sigma} t_2 : \kappa_2 \iff \min\{\bar{l} \mid t_1 : \kappa_1 \text{ rooted in } \Sigma \text{ at } \bar{l}\} \leq \min\{\bar{l} \mid t_2 : \kappa_2 \text{ rooted in } \Sigma \text{ at } \bar{l}\}$$

Signature normalization:

$$\begin{aligned} &\frac{\text{norm}_0(\tau) = \tau'}{\text{norm}([\tau]) = [\tau']} \\ &\frac{}{\text{norm}([= \tau : \kappa]) = [= \tau : \kappa]} \\ &\frac{}{\text{norm}(\Xi) = \Xi'} \\ &\frac{}{\text{norm}([= \Xi]) = [= \Xi']} \\ &\frac{\bigwedge_X \text{norm}(\Sigma_X) = \Sigma'_X}{\text{norm}(\{\overline{l}_X : \Sigma_X\}) = \{\overline{l}_X : \Sigma'_X\}} \\ &\frac{\text{sort}_{\leq_{\Sigma'}}(\overline{t : \kappa}) = \overline{t' : \kappa'} \quad \text{norm}(\Sigma) = \Sigma' \quad \text{norm}(\Xi) = \Xi'}{\text{norm}(\forall \overline{t : \kappa}. \Sigma \rightarrow \Xi) = \forall \overline{t' : \kappa'}. \Sigma' \rightarrow \Xi'} \\ &\frac{\text{sort}_{\leq_{\Sigma'}}(\overline{t : \kappa}) = \overline{t' : \kappa'} \quad \text{norm}(\Sigma) = \Sigma'}{\text{norm}(\exists \overline{t : \kappa}. \Sigma) = \exists \overline{t' : \kappa'}. \Sigma'} \end{aligned}$$

Type:

$$\boxed{\Gamma \vdash T : \kappa \rightsquigarrow \tau}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Xi}{\Gamma \vdash \text{pack } S : \Omega \rightsquigarrow \text{norm}(\Xi)} \text{ T-Pack}$$

Expression:

$$\boxed{\Gamma \vdash E : \tau \rightsquigarrow e}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Xi \quad \Gamma \vdash \Xi' \leq \text{norm}(\Xi) \rightsquigarrow e_1 \quad \Gamma \vdash M : \Xi' \rightsquigarrow e_2}{\Gamma \vdash (\text{pack } M : S) : \text{norm}(\Xi) \rightsquigarrow e_1 e_2} \text{E-Pack}$$

Module:

$$\boxed{\Gamma \vdash M : \Xi \rightsquigarrow e}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Xi \quad \Gamma \vdash E : \text{norm}(\Xi) \rightsquigarrow e}{\Gamma \vdash (\text{unpack } E : S) : \text{norm}(\Xi) \rightsquigarrow e} \text{M-Unpack}$$

4.2.6 Elaboration with Applicative Functor

$$\begin{aligned} S &::= \dots \\ &| (X : S) \Rightarrow S \quad (\text{applicative functor signature}) \end{aligned}$$

$$\begin{aligned} \varphi &::= I && (\text{impure effect}) \\ &| P && (\text{pure effect}) \\ \Sigma &::= \dots \\ &| \overline{\{l_X : \Sigma\}} \\ &| \forall t : \kappa. \Sigma \rightarrow_I \Xi \quad (\text{generative functor signature}) \\ &| \forall t : \kappa. \Sigma \rightarrow_P \Sigma \quad (\text{applicative functor signature}) \end{aligned}$$

Abbreviation:

$$\begin{aligned} \tau_1 \rightarrow_{\varphi} \tau_2 &\stackrel{\text{def}}{=} \tau_1 \rightarrow \{l_{\varphi} : \tau_2\} \\ \lambda_{\varphi} x : \tau. e &\stackrel{\text{def}}{=} \lambda x : \tau. \{l_{\varphi} = e\} \\ (e_1 e_2)_{\varphi} &\stackrel{\text{def}}{=} (e_1 e_2).l_{\varphi} \\ \Gamma^{\varphi} &\stackrel{\text{def}}{=} \begin{cases} \cdot & (\varphi = I) \\ \Gamma & (\varphi = P) \end{cases} \\ \text{tyenv}(\Gamma) &\stackrel{\text{def}}{=} \begin{cases} \text{tyenv}(\Gamma') \, t : \kappa & (\Gamma = \Gamma', t : \kappa) \\ \text{tyenv}(\Gamma') & (\Gamma = \Gamma', x : \tau) \\ \epsilon & (\Gamma = \cdot) \end{cases} \\ \forall_P \Gamma. \tau_0 &\stackrel{\text{def}}{=} \begin{cases} \forall_P \Gamma'. \forall t : \kappa. \tau_0 & (\Gamma = \Gamma', t : \kappa) \\ \forall_P \Gamma'. \tau \rightarrow_P \tau_0 & (\Gamma = \Gamma', x : \tau) \\ \tau_0 & (\Gamma = \cdot) \end{cases} \\ \Lambda_P \Gamma. e &\stackrel{\text{def}}{=} \begin{cases} \Lambda_P \Gamma'. \Lambda t : \kappa. e & (\Gamma = \Gamma', t : \kappa) \\ \Lambda_P \Gamma'. \lambda_P x : \tau. e & (\Gamma = \Gamma', x : \tau) \\ e & (\Gamma = \cdot) \end{cases} \\ (e \, \Gamma)_P &\stackrel{\text{def}}{=} \begin{cases} (e \, \Gamma')_P \, t & (\Gamma = \Gamma', t : \kappa) \\ ((e \, \Gamma')_P \, x)_P & (\Gamma = \Gamma', x : \tau) \\ e & (\Gamma = \cdot) \end{cases} \end{aligned}$$

Effect combining:

$$\boxed{\varphi_1 \vee \varphi_2 = \varphi}$$

$$\overline{\varphi \vee \varphi} = \varphi \quad \overline{I \vee P} = I \quad \overline{P \vee I} = I$$

Subeffects:

$$\varphi_1 \leq \varphi_2$$

$$\overline{\varphi \leq \varphi} \text{ F-Refl} \quad \overline{P \leq I} \text{ F-Sub}$$

Signature:

$$\Gamma \vdash S \rightsquigarrow \Xi$$

$$\frac{\Gamma \vdash S_1 \rightsquigarrow \exists \overline{t_1 : \kappa_1}. \Sigma \quad \Gamma, \overline{t_1 : \kappa_1}, x_X : \Sigma \vdash S_2 \rightsquigarrow \Xi}{\Gamma \vdash (X : S_1) \rightarrow S_2 \rightsquigarrow \forall \overline{t_1 : \kappa_1}. \Sigma \rightarrow_I \Xi} \text{ S-Funct-I}$$

$$\frac{\Gamma \vdash S_1 \rightsquigarrow \exists \overline{t_1 : \kappa_1}. \Sigma_1 \quad \Gamma, \overline{t_1 : \kappa_1}, x_X : \Sigma_1 \vdash S_2 \rightsquigarrow \exists \overline{t_2 : \kappa_2}. \Sigma_2}{\Gamma \vdash (X : S_1) \Rightarrow S_2 \rightsquigarrow \exists \overline{t'_2 : \kappa_1} \rightarrow \kappa_2. \forall \overline{t_1 : \kappa_1}. \Sigma_1 \rightarrow_P \Sigma_2[t_2 \leftarrow t'_2 \overline{t_1}]} \text{ S-Funct-P}$$

Subtyping:

$$\Gamma \vdash \Xi_1 \leq \Xi_2 \rightsquigarrow e$$

$$\frac{\Gamma, \overline{t_2 : \kappa_2} \vdash \Sigma_2 \leq \exists \overline{t_1 : \kappa_1}. \Sigma_1 \uparrow \overline{\tau} \rightsquigarrow e_1 \quad \Gamma, \overline{t_2 : \kappa_2} \vdash \Xi_1[\overline{t_1 \leftarrow \tau}] \leq \Xi_2 \rightsquigarrow e_2 \quad \varphi_1 \leq \varphi_2}{\Gamma \vdash (\forall \overline{t_1 : \kappa_1}. \Sigma_1 \rightarrow_{\varphi_1} \Xi_1) \leq (\forall \overline{t_2 : \kappa_2}. \Sigma_2 \rightarrow_{\varphi_2} \Xi_2) \rightsquigarrow \frac{\lambda x_1 : (\forall \overline{t_1 : \kappa_1}. \Sigma_1 \rightarrow_{\varphi_1} \Xi_1). \Lambda \overline{t_2 : \kappa_2}. \lambda_{\varphi_2} x_2 : \Sigma_2. e_2 (x_1 \overline{\tau} (e_1 x_2))_{\varphi_1}}{\text{U-Funct}}}$$

Module:

$$\Gamma \vdash M :_{\varphi} \Xi \rightsquigarrow e$$

$$\frac{\Gamma(x_X) = \Sigma}{\Gamma \vdash X :_P \Sigma \rightsquigarrow \Lambda_P \Gamma. x_X} \text{ M-Var}$$

$$\frac{\Gamma \vdash B :_{\varphi} \Xi \rightsquigarrow e}{\Gamma \vdash \{B\} :_{\varphi} \Xi \rightsquigarrow e} \text{ M-Struct}$$

$$\frac{\Gamma \vdash M :_{\varphi} \exists \overline{t : \kappa}. \{l_X : \Sigma, \overline{l_{X'}} : \Sigma'\} \rightsquigarrow e}{\Gamma \vdash M.X :_{\varphi} \exists \overline{t : \kappa}. \Sigma \rightsquigarrow \text{unpack} \langle \overline{t : \kappa}, x \rangle = e \text{ in } \text{pack} \langle \overline{t}, \Lambda_P \Gamma^{\varphi}. (x \Gamma^{\varphi})_P. l_X \rangle} \text{ M-Dot}$$

$$\frac{\Sigma \vdash S \rightsquigarrow \exists \overline{t : \kappa}. \Sigma \quad \Gamma, \overline{t : \kappa}, x_X : \Sigma \vdash M :_I \Xi \rightsquigarrow e}{\Gamma \vdash \text{fun } X : S \Rightarrow M :_P \forall \overline{t : \kappa}. \Sigma \rightarrow_I \Xi \rightsquigarrow \Lambda_P \Gamma. \Lambda \overline{t : \kappa}. \lambda_1 x_X : \Sigma. e} \text{ M-Funct-I}$$

$$\frac{\Sigma \vdash S \rightsquigarrow \exists \overline{t : \kappa}. \Sigma \quad \Gamma, \overline{t : \kappa}, x_X : \Sigma \vdash M :_P \exists \overline{t_2 : \kappa_2}. \Sigma_2 \rightsquigarrow e}{\Gamma \vdash \text{fun } X : S \Rightarrow M :_P \exists \overline{t_2 : \kappa_2}. \forall \overline{t : \kappa}. \Sigma \rightarrow_P \Sigma_2 \rightsquigarrow e} \text{ M-Funct-P}$$

$$\frac{\Gamma(x_{X_1}) = \forall \overline{t : \kappa}. \Sigma' \rightarrow_{\varphi} \Xi \quad \Gamma(x_{X_2}) = \Sigma \quad \Gamma \vdash \Sigma \leq \exists \overline{t : \kappa}. \Sigma' \uparrow \overline{\tau} \rightsquigarrow e}{\Gamma \vdash X_1 X_2 :_{\varphi} \Xi[\overline{t \leftarrow \tau}] \rightsquigarrow \Lambda_P \Gamma^{\varphi}. (x_{X_1} \overline{\tau} (e x_{X_2}))_{\varphi}} \text{ M-App}$$

$$\frac{\overline{t_{\Gamma} : \kappa_{\Gamma}} = \text{tyenv}(\Gamma) \quad \Gamma(x_X) = \Sigma \quad \Gamma \vdash S \rightsquigarrow \exists \overline{t : \kappa}. \Sigma' \quad \Gamma \vdash \Sigma \leq \exists \overline{t : \kappa}. \Sigma' \uparrow \overline{\tau} \rightsquigarrow e}{\Gamma \vdash X :> S :_P \exists \overline{t' : \overline{t_{\Gamma} : \kappa_{\Gamma}}} \rightarrow \kappa. \Sigma'[t \leftarrow t' \overline{t_{\Gamma}}] \rightsquigarrow \text{pack} \langle \lambda \overline{t_{\Gamma} : \kappa_{\Gamma}}. \tau, \Lambda_P \Gamma. e x_X \rangle} \text{ M-Seal}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Xi \quad \Gamma \vdash E : \text{norm}(\Xi) \rightsquigarrow e}{\Gamma \vdash (\text{unpack } E : S) :_I \text{norm}(\Xi) \rightsquigarrow e} \text{ M-Unpack}$$

定理 30 (Typing for module elaboration).

- $\Gamma \vdash M :_I \Xi \rightsquigarrow e$ ならば, $\Gamma \vdash e : \Xi$.
- $\Gamma \vdash M :_P \exists \overline{t : \kappa}. \Sigma \rightsquigarrow e$ ならば, $\cdot \vdash e : \exists \overline{t : \kappa}. \forall_P \Gamma. \Sigma$.

□

Bindings:

$$\Gamma \vdash B :_{\varphi} \Xi \rightsquigarrow e$$

$$\begin{array}{c}
\frac{\Gamma \vdash E : \tau \rightsquigarrow e}{\Gamma \vdash \text{val } X = E :_{\mathbf{P}} \{l_X : [\tau]\} \rightsquigarrow \Lambda_{\mathbf{P}}\Gamma.\{l_X = e\}} \text{ B-Val} \\
\frac{\Gamma \vdash T : \kappa \rightsquigarrow \tau}{\Gamma \vdash \text{type } X = T :_{\mathbf{P}} \{l_X : [\tau : \kappa]\} \rightsquigarrow \Lambda_{\mathbf{P}}\Gamma.\{l_X = [\tau : \kappa]\}} \text{ B-Typ} \\
\frac{\Gamma \vdash M :_{\varphi} \exists \overline{t} : \overline{\kappa}. \Sigma \rightsquigarrow e \quad \text{NotAtomic}(\Sigma)}{\Gamma \vdash \text{module } X = M :_{\varphi} \exists \overline{t} : \overline{\kappa}. \{l_X : \Sigma\} \rightsquigarrow \text{unpack}\langle \overline{t} : \overline{\kappa}, x \rangle = e \text{ in pack}\langle \overline{t}, \Lambda_{\mathbf{P}}\Gamma^{\varphi}.\{l_X = x \Gamma^{\varphi}\} \rangle} \text{ B-Mod} \\
\frac{\Gamma \vdash S \rightsquigarrow \Xi}{\Gamma \vdash \text{signature } X = S :_{\mathbf{P}} \{l_X : [\Xi]\} \rightsquigarrow \Lambda_{\mathbf{P}}\Gamma.\{l_X = [\Xi]\}} \text{ B-Sig} \\
\frac{\Gamma \vdash M :_{\varphi} \exists \overline{t} : \overline{\kappa}. \{l_X : \Sigma\} \rightsquigarrow e}{\Gamma \vdash \text{include } M :_{\varphi} \exists \overline{t} : \overline{\kappa}. \{l_X : \Sigma\} \rightsquigarrow e} \text{ B-Incl} \\
\frac{}{\Gamma \vdash \epsilon :_{\mathbf{P}} \{\} \rightsquigarrow \Lambda_{\mathbf{P}}\Gamma.\{\}} \text{ B-Emt} \\
\frac{\overline{l'_{X_1}} = \overline{l_{X_1}} \setminus \overline{l_{X_2}} \quad \overline{l'_{X_1}} : \Sigma'_1 \subseteq \overline{l_{X_1}} : \Sigma_1 \quad \Gamma \vdash B_1 :_{\varphi_1} \exists \overline{t_1} : \overline{\kappa_1}. \{l_{X_1} : \Sigma_1\} \rightsquigarrow e_1 \quad \Sigma = \{\overline{l'_{X_1}} : \Sigma'_1, \overline{l_{X_2}} : \Sigma_2\} \quad \Gamma, \overline{t_1} : \overline{\kappa_1}, \overline{x_{X_1}} : \overline{\Sigma_1} \vdash B_2 :_{\varphi_2} \exists \overline{t_2} : \overline{\kappa_2}. \{l_{X_2} : \Sigma_2\} \rightsquigarrow e_2}{\Gamma \vdash B_1; B_2 :_{\varphi_1 \vee \varphi_2} \exists \overline{t_1} : \overline{\kappa_1} \overline{t_2} : \overline{\kappa_2}. \Sigma \rightsquigarrow \text{unpack}\langle \overline{t_1} : \overline{\kappa_1}, x_1 \rangle = e_1 \text{ in } \text{unpack}\langle \overline{t_2} : \overline{\kappa_2}, x_2 \rangle = (\text{let } x_{X_1} = \Lambda_{\mathbf{P}}\Gamma^{\varphi_1 \vee \varphi_2}. (x_1 \Gamma^{\varphi_1})_{\mathbf{P}}. l_{X_1} \text{ in } e_2) \text{ in } \text{pack}\langle \overline{t_1} \overline{t_2}, \Lambda_{\mathbf{P}}\Gamma^{\varphi_1 \vee \varphi_2}. \text{let } x_{X_1} = (x_1 \Gamma^{\varphi_1})_{\mathbf{P}}. l_{X_1} \text{ in } \{l'_{X_1} = (x_1 \Gamma^{\varphi_1})_{\mathbf{P}}. l'_{X_1}, l_{X_2} = (x_2 (\Gamma, \overline{t_1} : \overline{\kappa_1}, \overline{x_{X_1}} : \overline{\Sigma_1})^{\varphi_2})_{\mathbf{P}}. l_{X_2}\} \rangle} \text{ B-Seq}
\end{array}$$

Path:

$$\boxed{\Gamma \vdash P : \Sigma \rightsquigarrow e}$$

$$\frac{\Gamma \vdash P :_{\varphi} \exists \overline{t} : \overline{\kappa}. \Sigma \quad \Gamma \vdash \Sigma : \Omega}{\Gamma \vdash P : \Sigma \rightsquigarrow \text{unpack}\langle \overline{t} : \overline{\kappa}, x \rangle = e \text{ in } (x \Gamma^{\varphi})_{\mathbf{P}}} \text{ P-Mod}$$

Expression:

$$\boxed{\Gamma \vdash E : \tau \rightsquigarrow e}$$

$$\frac{\Gamma \vdash S \rightsquigarrow \Xi \quad \Gamma \vdash \exists \overline{t} : \overline{\kappa}. \Sigma \leq \text{norm}(\Xi) \rightsquigarrow e_1 \quad \Gamma \vdash M :_{\varphi} \exists \overline{t} : \overline{\kappa}. \Sigma \rightsquigarrow e_2}{\Gamma \vdash (\text{pack } M : S) : \text{norm}(\Xi) \rightsquigarrow e_1 \text{ (unpack}\langle \overline{t} : \overline{\kappa}, x \rangle = e_2 \text{ in pack}\langle \overline{t} : \overline{\kappa}, (x \Gamma^{\varphi})_{\mathbf{P}} \rangle)} \text{ E-Unpack}$$

第 5 章

Control Operators

第 6 章

Implicit Parameters and Coherence

第 7 章

Records and Polymorphism

第 8 章

Type Checking and Inference

8.1 Hindley/Milner Type System

[LY98]

8.1.1 Language

$$X = \{x, y, z, \dots\}, \mathcal{A} = \{\alpha, \beta, \dots\}$$

E

$$\begin{aligned} e ::= & () \\ & | x \\ & | \lambda x. e \\ & | e e \\ & | \mathbf{let} \ x = e \ \mathbf{in} \ e \\ & | \mathbf{fix} \ f \ \lambda x. e \end{aligned}$$

T

$$\begin{aligned} \tau ::= & \mathbf{unit} \\ & | \alpha \\ & | \tau \rightarrow \tau \end{aligned}$$

Σ

$$\sigma ::= \forall \vec{\alpha}. \sigma$$

$$\Gamma = \mathcal{A} \xrightarrow{\text{fin}} \Sigma$$

8.1.2 Type System

$$\forall \vec{\alpha}. \tau_1 > \tau_2 \iff \exists S. S(\tau_1) = \tau_2 \wedge \text{dom}(S)$$

$$\text{Gen}(\Gamma, \tau) = \forall \vec{\alpha}. \tau$$

$$(\vec{\alpha} = \text{ftv}(\tau) \setminus \text{ftv}(\Gamma))$$

$$\begin{array}{c} \overline{\Gamma \vdash () : \mathbf{unit}} \\ \frac{\Gamma(x) > \tau}{\Gamma \vdash x : \tau} \\ \frac{\Gamma + x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x. e : \tau_1 \rightarrow \tau_2} \\ \frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau} \\ \frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma + x : \text{Gen}(\Gamma, \tau_1) \vdash e_2 : \tau}{\Gamma \vdash \mathbf{let} \ x = e_1 \ \mathbf{in} \ e_2 : \tau} \\ \frac{\Gamma + f : \tau \vdash \lambda x. e : \tau}{\Gamma \vdash \mathbf{fix} \ f \ \lambda x. e : \tau} \end{array}$$

第 3.1 節

定理 31. $\mathcal{U}(\tau_1, \tau_2) = S$ ならば, $S(\tau_1) = S(\tau_2)$.

□

8.1.3 Algorithm W

定理 32. 以下は同値

- $\mathcal{U}(\tau_1, \tau_2) = S$ を満たす S が存在する.
- $S(\tau_1) = S(\tau_2)$ を満たす S が存在する.

□

$$\begin{array}{c}
\overline{\mathcal{W}(\Gamma, ()) = (\emptyset, \mathbf{unit})} \\
\frac{\Gamma(x) = \forall \vec{\alpha}. \tau \quad \text{fresh } \vec{\beta}}{\mathcal{W}(\Gamma, x) = (\emptyset, [\vec{\alpha} \leftarrow \vec{\beta}]\tau)} \\
\frac{\text{fresh } \beta \quad \mathcal{W}(\Gamma + x : \beta, e) = (S_1, \tau_1)}{\mathcal{W}(\Gamma, \lambda x. e) = (S_1, S_1(\beta) \rightarrow \tau_1)} \\
\frac{\mathcal{W}(\Gamma, e_1) = (S_1, \tau_1) \quad \mathcal{W}(S_1(\Gamma), e_2) = (S_2, \tau_2) \quad \text{fresh } \beta \quad \mathcal{U}(S_2(\tau_1), \tau_2 \rightarrow \beta) = S_3}{\mathcal{W}(\Gamma, e_1 e_2) = (S_3 S_2 S_1, S_3(\beta))} \\
\frac{\mathcal{W}(\Gamma, e_1) = (S_1, \tau_1) \quad \Gamma_1 = S_1(\Gamma) \quad \mathcal{W}(\Gamma_1 + x : \text{Gen}(\Gamma_1, \tau_1), e_2) = (S_2, \tau_2)}{\mathcal{W}(\Gamma, \mathbf{let } x = e_1 \mathbf{ in } e_2) = (S_2 S_1, \tau_2)} \\
\frac{\text{fresh } \beta \quad \mathcal{W}(\Gamma + f : \beta, \lambda x. e) = (S_1, \tau_1) \quad \mathcal{U}(S_1(\beta), \tau_1) = S_2}{\mathcal{W}(\Gamma, \mathbf{fix } f \lambda x. e) = (S_2 S_1, S_2(\tau_1))}
\end{array}$$

定理 33. 以下は同値

- $\mathcal{W}(\Gamma_0, e) = (S, \tau_0)$, $S(\Gamma_0) = \Gamma$, $S(\tau_0) = \tau$ を満たす S , Γ_0 , τ_0 が存在する.
- $\Gamma \vdash e : \tau$.

□

8.1.4 Algorithm M

$$\begin{array}{c}
\frac{\mathcal{U}(\rho, \mathbf{unit}) = S}{\mathcal{M}(\Gamma, (), \rho) = S} \\
\frac{\mathcal{U}(\rho, [\vec{\beta} \leftarrow \vec{\alpha}]\tau) = S \quad \Gamma(x) = \forall \vec{\alpha}. \tau \quad \text{fresh } \vec{\beta}}{\mathcal{M}(\Gamma, x, \rho) = S} \\
\frac{\mathcal{U}(\rho, \beta_1 \rightarrow \beta_2) = S_1 \quad \text{fresh } \beta_1, \beta_2 \quad \mathcal{M}(S_1(\Gamma) + x : S_1(\beta_1), e, S_1(\beta_2)) = S_2}{\mathcal{M}(\Gamma, \lambda x. e, \rho) = S_2 S_1} \\
\frac{\mathcal{M}(\Gamma, e_1, \beta \rightarrow \rho) = S_1 \quad \text{fresh } \beta \quad \mathcal{M}(S_1(\Gamma), e_2, S_1(\beta)) = S_2}{\mathcal{M}(\Gamma, e_1 e_2, \rho) = S_2 S_1} \\
\frac{\mathcal{M}(\Gamma, e_1, \beta) = S_1 \quad \text{fresh } \beta \quad \mathcal{M}(S_1(\Gamma) + x : \text{Gen}(\Gamma, S_1(\beta)), e_2, S_1(\rho)) = S_2}{\mathcal{M}(\Gamma, \mathbf{let } x = e_1 \mathbf{ in } e_2, \rho) = S_2 S_1} \\
\frac{\mathcal{M}(\Gamma + f : \rho, \lambda x. e, \rho) = S}{\mathcal{M}(\Gamma, \mathbf{fix } f \lambda x. e, \rho) = S}
\end{array}$$

定理 34. 以下は同値

- $\mathcal{M}(\Gamma_0, e, \rho) = S$, $S(\Gamma_0) = \Gamma$, $S(\rho) = \tau$ を満たす S , Γ_0 , ρ が存在する.
- $\Gamma \vdash e : \tau$.

□

8.1.5 Alternative Type System

$$\begin{array}{c}
\overline{\Gamma \vdash () : \mathbf{unit}} \\
\frac{\Gamma(x) = \sigma}{\Gamma \vdash x : \sigma} \\
\frac{\Gamma + x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x. e : \tau_1 \rightarrow \tau_2} \\
\frac{\Gamma \vdash e_1 : \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau} \\
\frac{\Gamma \vdash e_1 : \sigma_1 \quad \Gamma + x : \sigma_1 \vdash e_2 : \tau}{\Gamma \vdash \mathbf{let} x = e_1 \mathbf{in} e_2 : \tau} \\
\frac{\Gamma + f : \tau \vdash \lambda x. e : \tau}{\Gamma \vdash \mathbf{fix} f \lambda x. e : \tau} \\
\frac{\Gamma \vdash e : \tau \quad \vec{\alpha} \notin \text{ftv}(\tau)}{\Gamma \vdash e : \forall \vec{\alpha}. \tau} \\
\frac{\Gamma \vdash e : \forall \vec{\alpha}. \tau}{\Gamma \vdash e : [\vec{\alpha} \leftarrow \vec{\tau}'] \tau}
\end{array}$$

8.2 WIP: HM(X): HM Type System with Constraint System

[OSW99][EL04]

8.2.1 Constraint System

定義 35 (単純制約システム (simple constraint system)). 単純制約システムとは, 以下の組 (Ω, \Vdash) のこと.

- 非空のアルファベット Ω .
- 関係 $(\Vdash) \subseteq \mathcal{P}(\Omega) \times \Omega$ で, 以下を満たすもの.
 - 任意の $C \in \mathcal{P}(\Omega)$, $P \in C$ について, $C \Vdash P$.
 - 任意の $C, D \in \mathcal{P}(\Omega)$, $Q \in \Omega$ について, $(\forall P \in D. C \Vdash P)$ かつ $D \Vdash Q$ ならば $C \Vdash Q$.

この時, $C \in \mathcal{P}(\Omega)$ を制約 (*constraint*) と呼ぶ. また, $(\Vdash) \subseteq (\mathcal{P}(\Omega))^2$ への拡張を, $C \Vdash D \stackrel{\text{def}}{\iff} \forall P \in D. C \Vdash P$ と定義する. $C \Vdash D$ かつ $D \Vdash C$ の時, $C \dashv\vdash D$ と表記する. □

第 9 章

Static Memory Management and Regions

第 10 章

Dynamic Memory Management and Gabage Collections

第 11 章

I/O Management and Concurrency

第 12 章

Code Generation and Virtual Machines

第 13 章

Program Stability and Compatibility

第 14 章

Program Separation and Linking

第 15 章

Syntax and Parsing

15.1 WIP: Parsing by LR Method

[Knu65]

15.2 Syntax and Semantics of PEG

[For02], [For04]

15.2.1 Syntax

| | | |
|--------------|------------|-----------------|
| $e ::=$ | ϵ | (epsilon) |
| | $ \sigma$ | (terminal) |
| | $ A$ | (non-terminal) |
| | $ ee$ | (sequence) |
| | $ e / e$ | (alternative) |
| | $ e^*$ | (repetition) |
| | $!e$ | (not predicate) |
| $\sigma \in$ | Σ | |
| $A \in$ | N | |

定義 36. PEG 文法とは、以下による組 $G = (\Sigma, N, R, e_0)$ のことである。

Σ 終端記号の集合.

N 非終端記号の集合.

R $A \rightarrow e$ を満たす規則の集合. 規則は、非終端記号に対して必ず一つ.

e_0 初期式.

□

15.2.2 Structured Semantics

$$\begin{array}{c}
 \overline{\langle \epsilon, x \rangle \rightarrow s(\epsilon)} \\
 \overline{\langle \sigma, \sigma x \rangle \rightarrow s(\sigma)} \quad \overline{\langle \sigma, \sigma' x \rangle \rightarrow f} \quad \overline{\langle \sigma, \epsilon \rangle \rightarrow f} \quad \overline{\langle A, x \rangle \rightarrow o} \\
 \overline{\langle e, x \rangle \rightarrow o} \\
 \overline{\langle e_1, x_1 x_2 y \rangle \rightarrow s(x_1)} \quad \overline{\langle e_2, x_2 y \rangle \rightarrow s(x_2)} \quad \overline{\langle e_1, x \rangle \rightarrow f} \quad \overline{\langle e_1, x_1 y \rangle \rightarrow s(x_1)} \quad \overline{\langle e_2, y \rangle \rightarrow f} \\
 \overline{\langle e_1 e_2, x_1 x_2 y \rangle \rightarrow s(x_1 x_2)} \quad \overline{\langle e_1 e_2, x \rangle \rightarrow f} \quad \overline{\langle e_1 e_2, x_1 y \rangle \rightarrow f} \\
 \overline{\langle e_1, xy \rangle \rightarrow s(x)} \quad \overline{\langle e_1, x \rangle \rightarrow f} \quad \overline{\langle e_2, x \rangle \rightarrow o} \\
 \overline{\langle e_1 / e_2, xy \rangle \rightarrow s(x)} \quad \overline{\langle e_1 / e_2, x \rangle \rightarrow o} \\
 \overline{\langle e, x_1 x_2 y \rangle \rightarrow s(x_1)} \quad \overline{\langle e^*, x_2 y \rangle \rightarrow s(x_2)} \quad \overline{\langle e, x \rangle \rightarrow f} \\
 \overline{\langle e^*, x_1 x_2 y \rangle \rightarrow s(x_1 x_2)} \quad \overline{\langle e^*, x \rangle \rightarrow s(\epsilon)} \\
 \overline{\langle e, x \rangle \rightarrow f} \quad \overline{\langle e, xy \rangle \rightarrow s(x)} \\
 \overline{\langle !e, x \rangle \rightarrow s(\epsilon)} \quad \overline{\langle !e, xy \rangle \rightarrow f}
 \end{array}$$

$$\llbracket (\Sigma, N, R, e_0) \rrbracket = \llbracket e_0 \rrbracket$$

$$\llbracket e \rrbracket = \{x \in \Sigma^* \mid \langle e, x \rangle \rightarrow s(x)\}$$

15.2.3 Equivalence

Abbreviations

| | |
|--------------------|-----------------------|
| $\& e = !(e)$ | (and predicate) |
| $e^+ = ee^*$ | (positive repetition) |
| $e^? = e/\epsilon$ | (optional) |

Associativity

$$\overline{\llbracket e_1/(e_2/e_3) \rrbracket} = \overline{\llbracket (e_1/e_2)/e_3 \rrbracket}$$

$$\overline{\llbracket e_1(e_2e_3) \rrbracket} = \overline{\llbracket (e_1e_2)e_3 \rrbracket}$$

Epsilon

$$\overline{\llbracket \epsilon/e \rrbracket} = \overline{\llbracket \epsilon \rrbracket}$$

$$\overline{\llbracket e\epsilon \rrbracket} = \overline{\llbracket e \rrbracket} \quad \overline{\llbracket \epsilon e \rrbracket} = \overline{\llbracket e \rrbracket}$$

Repetition

$$M ::= eM \mid \epsilon$$

$$\overline{\llbracket e^* \rrbracket} = \overline{\llbracket M \rrbracket}$$

15.2.4 Producing Analysis

$$s ::= 0 \mid 1, \quad o ::= s \mid f$$

- $\epsilon \rightarrow 0$
- $\sigma \rightarrow 1$
- $\sigma \rightarrow f$
- $A \leftarrow e \in R, \quad e \rightarrow o \text{ ならば } A \rightarrow o$
- $e_1 \rightarrow 0, \quad e_2 \rightarrow 0 \text{ ならば } e_1e_2 \rightarrow 0$
- $e_1 \rightarrow 1, \quad e_2 \rightarrow s \text{ ならば } e_1e_2 \rightarrow 1$
- $e_1 \rightarrow s, \quad e_2 \rightarrow 1 \text{ ならば } e_1e_2 \rightarrow 1$
- $e_1 \rightarrow f \text{ ならば } e_1e_2 \rightarrow f$
- $e_1 \rightarrow s, \quad e_2 \rightarrow f \text{ ならば } e_1e_2 \rightarrow f$
- $e_1 \rightarrow s \text{ ならば } e_1 / e_2 \rightarrow s$
- $e_1 \rightarrow f, \quad e_2 \rightarrow o \text{ ならば } e_1 / e_2 \rightarrow o$
- $e \rightarrow 1 \text{ ならば } e^* \rightarrow 1$
- $e \rightarrow f \text{ ならば } e^* \rightarrow f$
- $e \rightarrow s \text{ ならば } !e \rightarrow f$

- $e \rightarrow f$ ならば $e \rightarrow 0$

定理 37.

- $\langle e, x \rangle \rightarrow s(\epsilon)$ ならば, $e \rightarrow 0$
- $\langle e, xy \rangle \rightarrow s(x)$, $x \neq \epsilon$ ならば, $e \rightarrow 1$
- $\langle e, x \rangle \rightarrow f$ ならば, $e \rightarrow f$

□

系 38. $e \not\rightarrow 0$ ならば, $\langle e, xy \rangle \not\rightarrow s(x)$ かつ $\langle e, xy \rangle \not\rightarrow f$

□

15.3 Haskell Parsing with PEG

[Sim10]

15.3.1 Lexical Syntax

```

program ::= (lexeme | whitespace)*
lexeme  ::= qvarid
          | qconid
          | qvarsym
          | qconsym
          | literal
          | special
          | reservedop
          | reservedid
literal  ::= integer
          | float
          | char
          | string
special  ::= "(" | ")" | "," | ";" | "[" | "]" | "`" | "{" | "}"
whitespace ::= whitestuff+
whitestuff ::= whitechar | comment | ncomment

whitechar ::= newline | "\v" | " " | "\t" | (Unicode whitespace)
newline   ::= "\x\n" | "\r" | "\n" | "\f"
comment   ::= dashes (!symbol any*)? newline
dashes    ::= "-" ("-"+)
opencom   ::= "{-"
closecom  ::= "-}"
ncomment  ::= opencom ANYs (ncomment ANYs)* closecom
ANYs      ::= !(ANY* (opencom | closecom) ANY*) ANY*
ANY       ::= graphic | whitechar
any       ::= graphic | " " | "\t"
graphic   ::= small | large | symbol | digit | special | "\" | "'"
small     ::= "a" | "b" | ... | "z" | (Unicode lowercase letter) | "_"
large     ::= "A" | "B" | ... | "Z" | (Unicode uppercase letter) | (Unicode titlecase letter)
symbol    ::= "!" | "#" | "$" | "%" | "&" | "*" | "+" | "." | "/" | "<" | "=" | ">"
           | "?" | "@" | "\" | "^" | "|" | "-" | "~" | ":"
           | !(symbol | "_" | "\" | "'" | "`") uniSymbol
uniSymbol ::= (Unicode symbol) | (Unicode punctuation)
digit     ::= "0" | "1" | ... | "9" | (Unicode decimal digit)
octit     ::= "0" | "1" | ... | "7"
hexit     ::= digit | "A" | ... | "F" | "a" | ... | "f"
varid     ::= !(reservedid !other) small other*
conid     ::= large other*
other     ::= small | large | digit | "'"
reservedid ::= "case" | "class" | "data" | "default" | "deriving" | "do" | "else"
           | "foreign" | "if" | "import" | "in" | "infix" | "infixl" | "infixr"
           | "instance" | "let" | "module" | "newtype" | "of" | "then" | "type"
           | "where" | "_"
varsym    ::= !(reservedop | dashes) !symbol ":" symbol+
consym    ::= !(reservedop !symbol) ":" symbol+
reservedop ::= "." | ":" | "::" | "=" | "\\" | "<-" | "->" | "@" | "~" | "=>"

```

```

modid  ::= (conid "." )* conid
qvarid ::= (modid "." )? varid
qconid ::= (modid "." )? conid
qvarsym ::= (modid "." )? varsym
qconsym ::= (modid "." )? consym

decimal ::= digit+
octal   ::= octit+
hexadecimal ::= hexit+
integer ::= decimal
        | "0o" octal | "0O" octal
        | "0x" hexadecimal | "0X" hexadecimal
float   ::= decimal "." decimal exponent?
        | decimal exponent
exponent ::= ("e" | "E") ("+" | "-" ) decimal
char     ::= "'" (!("'" | "\\") graphic | " " | !"\\&" escape) "'"
string   ::= "\"" (!("\"" | "\\") graphic | " " | escape | gap)* "\""
escape   ::= "\\\"(charesc | ascii | decimal | "o" octal | "x" hexadecimal)
charesc  ::= "a" | "b" | "f" | "n" | "r" | "t" | "v" | "\\\" | "\\\" | "'" | "&"
ascii    ::= "^" cntrl | "NUL" | "SOH" | "STX" | "ETX" | "EOT" | "ENQ" | "ACK" | "BEL" | "BS"
        | "HT" | "LF" | "VT" | "FF" | "CR" | "SO" | "SI" | "DLE" | "DC1" | "DC2" | "DC3"
        | "DC4" | "NAK" | "SYN" | "ETB" | "CAN" | "EM" | "SUB" | "ESC" | "FS" | "GS" | "RS"
        | "US" | "SP" | "DEL"
cntrl    ::= "A" | "B" | ... | "Z" | "@" | "[" | "\\\" | "]" | "^" | "_"
gap      ::= "\\\" whitechar+ "\\\"

```

15.3.2 Preprocess for Layout

$$\begin{aligned}
L(s) &= \begin{cases} L_1(r', s) & (s = t : s', \text{pos}(t) = (r', c'), \text{islt}(t)) \\ \{c'\} : \langle c' \rangle : L_1(r', s) & (s = t : s', \text{pos}(t) = (r', c'), \text{islt}(t)) \\ \{1\} : \epsilon & (s = \epsilon) \end{cases} \\
L_1(r, s) &= \begin{cases} \langle c' \rangle : L_2(r', c', t, s') & (s = t : s', \text{pos}(t) = (r', c'), r \neq r') \\ L_2(r', c', t, s') & (s = t : s', \text{pos}(t) = (r', c'), r = r') \\ \epsilon & (s = \epsilon) \end{cases} \\
L_2(r_1, c_1, t_1, s) &= \begin{cases} t_1 : t_2 : L_1(r_2, s') & (\text{islt}(t_1), s = t_2 : s', \text{pos}(t_2) = (r_2, c_2), t_2 = "\{") \\ t_1 : \{c_2\} : \langle c_2 \rangle : t_2 : L_1(r_2, s') & (\text{islt}(t_1), s = t_2 : s', \text{pos}(t_2) = (r_2, c_2), t_2 \neq "\{") \\ t_1 : \{1\} : \epsilon & (\text{islt}(t_1), s = \epsilon) \\ t_1 : L_1(r_1, s) & (\text{islt}(t_1)) \end{cases} \\
\text{islt}(t) &= \begin{cases} \top & (t = \text{"module"}) \\ \perp & (\text{otherwise}) \end{cases} \\
\text{islt}(t) &= \begin{cases} \top & (t = \text{"let"}) \\ \top & (t = \text{"where"}) \\ \top & (t = \text{"do"}) \\ \top & (t = \text{"of"}) \\ \perp & (\text{otherwise}) \end{cases}
\end{aligned}$$

15.3.3 PEG with Layout Tokens

```

module  ::= "module" modid exports? "where" body
        | body
body    ::= expbo bodyinl expbc
        | impbo bodyinl impbc
bodyinl ::= impdecls semi+ topdecls
        | impdecls
        | topdecls

```

```

impdecls ::= semi*(impdecl semi+)* impdecl
exports ::= "(" (export " ,")* export? ")"
export  ::= qvar
        | qtycon "(" (" (". ." | (cname " ,")* cname)? ")" )?
        | "module" modid
impdecl ::= "import" "qualified"? modid ("as" modid)? impspec?
impspec ::= "(" (import " ,")* import? ")"
        | "hiding" "(" (import " ,")* import? ")"
import  ::= var
        | tycon "(" (" (". ." | (cname " ,")* cname)? ")" )?
cname   ::= var | con

topdecls ::= (topdecl semi)* topdecl |
topdecl  ::= "type" simpletype "=" type
        | "data" (context "=>")? simpletype ("=" constrs)? deriving?
        | "newtype" (context "=>")? simpletype "=" newconstr deriving?
        | "class" (scontext "=>")? tycon tyvar ("where" cdecls)?
        | "instance" (scontext "=>")? qtycon inst ("where" idecls)?
        | "default" "(" ((type " ,")* type)? ")"
        | "foreign" fdecl
        | decl

decls    ::= expbo declsinl expbc
        | impbo declsinl impbc
declsinl ::= (decl semi)* decl |
decl     ::= (funlhs | pat) rhs
        | gendecl
cdecls   ::= expbo cdeclsinl expbc
        | impbo cdeclsinl impbc
cdeclsinl ::= (cdecl semi)* cdecl |
cdecl    ::= (funlhs | var) rhs
        | gendecl
idecls   ::= expbo ideclsinl expbc
        | impbo ideclsinl impbc
ideclsinl ::= (idecl semi)* idecl |
idecl    ::= (funlhs | var) rhs
        |
gendecl  ::= vars " : : " (context "=>")? type
        | fixity integer? ops
        |
ops      ::= (op " ,")* op
vars     ::= (var " ,")* var
fixity   ::= "infixl" | "infixr" | "infix"

type     ::= btype ("->" type)?
btype    ::= btype? atype
atype    ::= gtycon
        | tyvar
        | "(" (type " ,")+ type ")"
        | "[" type "]"
        | "(" type ")"
gtycon   ::= qtycon
        | "(" " " ")"
        | "[" " " "]"
        | "(" " -> " " " ")"
        | "(" " , "+" " " ")"

```

```

context ::= class
        | "(" ((class " ," )* class)? ")"
class   ::= qtycon tyvar
        | qtycon "(" tyvar atype+ ")"
scontext ::= simpleclass
        | "(" ((simpleclass " ," )* simpleclass)? ")"
simpleclass ::= qtycon tyvar

simpletype ::= tycon tyvar*
constrs  ::= (constr " | " )* constr
constr   ::= con expbo ((fielddecl " ," )* fielddecl)? expbc
        | (btype | " ! " atype) conop (btype | " ! " atype)
        | con (" ! " ? atype)*
newconstr ::= con expbo var " :: " type expbc
        | con atype
fielddecl ::= vars " :: " (type | " ! " atype)
deriving  ::= "deriving" dclass
        | "deriving" "(" ((dclass " ," )* dclass)? ")"
dclass    ::= qtycon
inst      ::= gtycon
        | "(" gtycon tyvar* ")"
        | "(" (tyvar " ," )+ tyvar ")"
        | "[" tyvar "]"
        | "(" tyvar "->" tyvar ")"

fdecl ::= "import" callconv safety? impent var " :: " ftype
        | "export" callconv expent var " :: " ftype
callconv ::= "ccall" | "stdcall" | "cplusplus" | "jvm" | "dotnet"
        | (system-specific calling conventions)
impent   ::= string?
expent   ::= string?
safety   ::= "unsafe" | "safe"
ftype    ::= fatype "->" ftype
        | frtype
frtype   ::= fatype
        | "(" " " ")"
fatype   ::= qtycon atype*

funlhs   ::= var apat+
        | pat varop pat
        | "(" funlhs " )" apat+
rhs      ::= "=" exp ("where" decls)?
        | gdrhs ("where" decls)?
gdrhs    ::= guards "=" exp gdrhs?
guards   ::= " | " (guard " ," )* guard |
guard    ::= pat "<-" infixexp
        | "let" decls
        | infixexp

```

```

exp ::= infixexp ":" (context "=>")? type
    | infixexp
infixexp ::= "-" infixexp
    | lexp qop infixexp
    | lexp
lexp ::= "\\\" apat+ "->" exp
    | "let" decls "in" exp
    | "if" exp semi? "then" exp semi? "else" exp
    | "case" exp "of" casealts
    | "do" dostmts
    | fexp
fexp ::= aexp+
aexp ::= qcon expbo ((fbind " ,")* fbind)? expbc
    | aexp2 (expbo ((fbind " ,")* fbind)? expbc)*
    | qvar
aexp2 ::= literal
    | "(" exp ")"
    | "(" (exp " ,")+ exp ")"
    | "[" (exp " ,")* exp "]"
    | "[" exp "(" exp )? ". ." exp? "]"
    | "[" exp " | " (qual " ,")* qual "]"
    | "(" infixexp qop ")"
    | "(" !("-" infixexp) qop infixexp ")"
    | gcon

```

```

qual ::= pat "<-" exp
    | "let" decls
    | exp
casealts ::= expbo alts expbc
    | impbo alts impbc
alts ::= (alt semi)* alt
alt ::= pat "->" exp ("where" decls)?
    | pat gdpat ("where" decls)?
    |
gdpat ::= guards "->" exp gdpat?
dostmts ::= expbo stmts expbc
    | impbo stmts impbc
stmts ::= stmt* exp semi?
stmt ::= exp semi
    | pat "<-" exp semi
    | "let" decls semi
    | semi
fbind ::= qvar "=" exp

```

```

pat ::= lpat qconop pat
    | lpat
lpat ::= "-" (integer | float)
    | gcon apat+
    | apat
apat ::= var ("@" apat)?
    | literal
    | "_"
    | "(" pat ")"
    | "(" (pat " ,")+ pat ")"
    | "[" (pat " ,")* pat "]"
    | "~" apat
    | qcon expbo ((fpat " ,")* fpat)? expbc
    | gcon
fpat ::= qvar "=" pat

```

```

gcon  ::= "(" ")"
      | "[" "]"
      | "(" " ", "+ " ")"
      | qcon
var    ::= varid | "(" varsym ")"
qvar   ::= qvarid | "(" qvarsym ")"
con    ::= conid | "(" consym ")"
qcon   ::= qconid | "(" gconsym ")"
varop  ::= varsym | "^" varid "^"
qvarop ::= qvarsym | "^" qvarid "^"
conop  ::= consym | "^" conid "^"
qconop ::= gconsym | "^" qconid "^"
op     ::= varop | conop
qop    ::= qvarop | qconop
gconsym ::= ":" | qconsym
tyvar  ::= varid
tycon  ::= conid
qtycon ::= qconid

```

```

expbo  ::= [l]      "{" [0 : l]
expbc  ::= [0 : l]  "}" [l]
impbo  ::= [m : l]  {n} [n : m : l | n > m]
        ::= [m : l]  {n} [(n + 1) : m : l | n ≤ m]
        | [ε]       {n} [n : ε | n > 0]
impbc  ::= [m : l]  ε [l | m > 0]
semi   ::= " ; "
        | [m : l]  ⟨n⟩ [m : l | m = n]

```

```

skip   ::= [m : l]  ⟨n⟩ [m : l | m < n]

```

15.4 WIP: A Memory Optimization for PEG with Cut Operations

[MMY08][MMY10]

15.5 WIP: SRB: An Abstract Machine of PEG

第 16 章

Analysis and Optimizations

第 17 章

Meta-Programming and Multi-Stage Programming

第 18 章

Generic Programming

第 19 章

Advanced Calculus

第 20 章

Quell: A Language for Functional Programming

20.1 WIP: Implementation Note of PEG Parser

Normalizing

$$\begin{aligned}
 e_{\text{RHS}} &::= e_1 / \dots / e_n / \epsilon & (n \in \mathbb{N}) \\
 &| e_1 / \dots / e_n & (n \in \mathbb{N}_{\geq 1}) \\
 e &::= !(u_1 \dots u_n) & (n \in \mathbb{N}_{\geq 1}) \\
 &| \&(u_1 \dots u_n) & (n \in \mathbb{N}_{\geq 1}) \\
 &| u_1 \dots u_n & (n \in \mathbb{N}_{\geq 1}) \\
 u &::= \sigma \\
 &| A
 \end{aligned}$$

$$\begin{aligned}
 \text{norm}(N, []) &= (N, \emptyset) \\
 \text{norm}(N, [A \leftarrow e] + X) &= (N_2, \{A \leftarrow \text{alt}(a)\} \cup X_1 \cup X_2) \\
 &(\text{norm}(N, e) = (a, N_1, X_1), \text{norm}(N_1, X) = (N_2, X_2))
 \end{aligned}$$

$$\begin{aligned}
 \text{norm}(N, \epsilon) &= ([\epsilon], N, \emptyset) \\
 \text{norm}(N, \sigma) &= ([\sigma], N, \emptyset) \\
 \text{norm}(N, A) &= ([A], N, \emptyset) \\
 \text{norm}(N, e_1 e_2) &= (\text{seq}(a_1, a_2), N_2, X_1 \cup X_2) & (\text{norm}(N, e_1) = (a_1, N_1, X_1), \text{norm}(N_1, e_2) = (a_2, N_2, X_2)) \\
 \text{norm}(N, e_1 / e_2) &= (a_1 + a_2, N_2, X_1 \cup X_2) & (\text{norm}(N, e_1) = (a_1, N_1, X_1), \text{norm}(N_1, e_2) = (a_2, N_2, X_2)) \\
 \text{norm}(N, e^*) &= ([M], N' \uplus \{M\}, X \cup \{M \leftarrow AM / \epsilon\}) & (\text{norm}(N \uplus \{A\}, [A \leftarrow e]) = (N', X)) \\
 \text{norm}(N, \& e) &= ([M], N' \uplus \{M\}, X \cup \{M \leftarrow \&A\}) & (\text{norm}(N + \{A\}, [A \leftarrow e]) = (N', X)) \\
 \text{norm}(N, ! e) &= ([M], N' \uplus \{M\}, X \cup \{M \leftarrow !A\}) & (\text{norm}(N + \{A\}, [A \leftarrow e]) = (N', X))
 \end{aligned}$$

$$\begin{aligned}
 \text{seq}(a_1, a_2) &= [e_1 e_2 \mid e_1 \leftarrow a_1, e_2 \leftarrow a_2] \\
 \text{alt}([e_1, \dots, e_n]) &= e_1 / \dots / e_n & (\forall i < m. e_i \neq \epsilon, e_m = \epsilon) \\
 \text{alt}([e_1, \dots, e_n]) &= e_1 / \dots / e_n & (\forall i. e_i \neq \epsilon)
 \end{aligned}$$

$$\begin{aligned}
 \text{norm}((\Sigma, N, R, e_0)) &= (\Sigma, N', R', S) \\
 (R = \{A_1 \leftarrow e_1, \dots, A_n \leftarrow e_n\}, \text{norm}(N \uplus \{S\}, [S \leftarrow e_0, A_1 \leftarrow e_1, \dots, A_n \leftarrow e_n])) &= (N', R')
 \end{aligned}$$

Machine

State:

- a rule
- current position in rule

Transition:

- σ
- EOS
- otherwise

Output:

with backpoint バックポイントを設置し、バックポイントに戻った時の次の遷移を指定する。fail した場合一番直近の backpoint まで入力状態とスタックを戻す。reduce 時取り除かれる。

enter 非終端記号を参照する。メモ化されている場合その値を使う。それ以外の場合、reduce 時戻ってくる状態を記録し、次の状態に遷移する。

goto 次の状態に遷移する。

shift 入力を 1 つ消費し、次の状態に遷移する。

reduce 規則に沿ってスタックから要素を取り出してまとめ、メモリ、スタックに新たに入れた後、enter 時に記録された状態に遷移する。

Optimization

1. unify transitions.
2. look ahead backpoints.

Example

$$\begin{array}{lcl}
 E & ::= & CA \\
 & | & \epsilon \\
 A & ::= & aB \\
 & | & a \\
 B & ::= & bA \\
 & | & b \\
 C & ::= & !abab \\
 & | & \& ab
 \end{array}$$

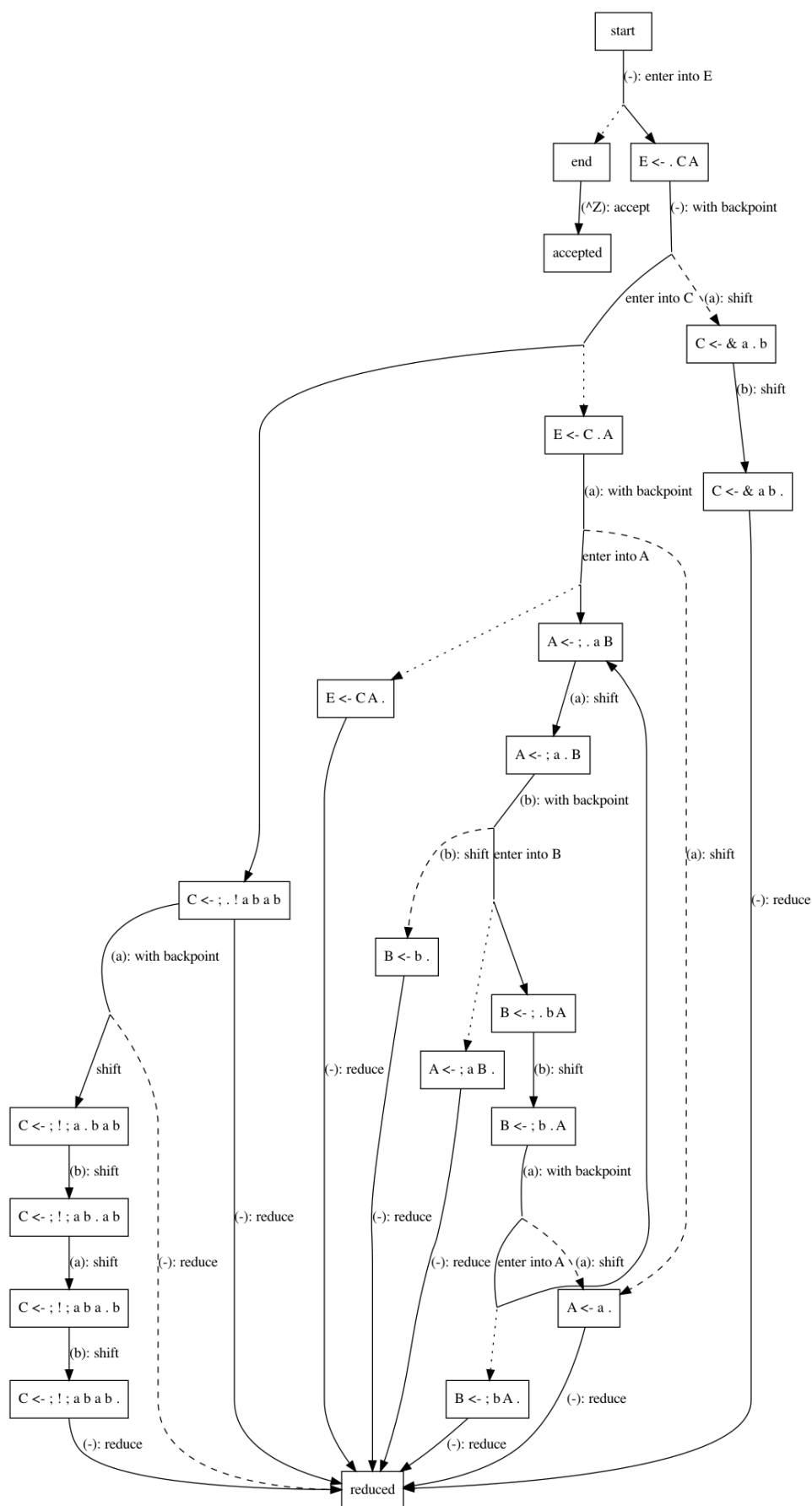


図 20.2 最適化された状態遷移図

20.2 Quell Syntax and Identations

20.2.1 Syntax

20.3 Quell Modules

20.3.1 Syntax

$$\begin{array}{ll}
 e & ::= \dots \\
 & \quad | \text{ letrec } \{B\} \text{ in } e \\
 & \quad | P \\
 \tau & ::= \dots \\
 & \quad | P \\
 P & ::= M \\
 M & ::= x \\
 & \quad | \{B\} \\
 & \quad | M.x \\
 & \quad | \text{ fun } x : S. M \\
 & \quad | x \ x \\
 & \quad | x : S \\
 B & ::= x = e \\
 & \quad | \text{ type } t = T \\
 & \quad | \text{ module } x = M \\
 & \quad | \text{ use } B \\
 & \quad | \epsilon \\
 & \quad | B; B \\
 T & ::= \lambda x. T \\
 & \quad | \tau \\
 S & ::= P \\
 & \quad | \{D\} \\
 & \quad | (x : S) \rightarrow S \\
 & \quad |
 \end{array}$$

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