

The Lambë programming language

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1 Kind level

m_i	\in	\mathcal{I}	Component name
κ	$=$	\star	Kind
	$ $	$\kappa \rightarrow \kappa$	Function Kind
	$ $	K	Trait Kind

$$K = \{m_i : \kappa_i\}_I$$

2 Type level

\underline{c}	\in	\mathcal{C}	Constructor names
α	\in	\mathcal{I}	Variable names
τ	$=$	α	Variable or Constant
	$ $	$\tau \rightarrow \tau$	Function Type
	$ $	$\tau \multimap \tau$	Method Type
	$ $	$\tau + \tau$	Sum type
	$ $	$\tau \tau$	Type Application
	$ $	$\Lambda(\alpha : \kappa).\tau$	Type Abstraction
	$ $	$\forall(\alpha : \kappa).\tau$	Universal Quantification
	$ $	$\exists(\alpha : \kappa).\tau$	Existential Quantification
	$ $	$\mu(\alpha : \kappa).\tau$	Type Recursion
	$ $	$\underline{c}S$	Type Constructor
	$ $	Γ	Trait Type
	$ $	$\tau.m$	Trait Type Usage

$$\begin{aligned} T &= \{m_i \triangleq \tau_i\}_I \\ S &= \{m_i : \tau_i\}_I \\ \Gamma &= \langle K, T, S, \{\Gamma_i\}_I \rangle \end{aligned}$$

3 Trait level

$$\begin{aligned}
\Gamma &= \langle K, T, S, \{\Gamma_i\}_I \rangle \\
\Gamma_\emptyset &= \langle \emptyset, \emptyset, \emptyset, \emptyset \rangle \\
- + - &: \Gamma \rightarrow \Gamma \rightarrow \Gamma \\
\Gamma_\emptyset + \Gamma' &= \Gamma' \\
\Gamma' + \Gamma_\emptyset &= \Gamma' \\
\langle K, T, S, W \rangle + \Gamma &= \langle K, T, S, W \cup \Gamma \rangle \\
-[-]_\kappa &: \Gamma \rightarrow \kappa + \perp \\
\langle \{n_i : k_i\}_I, \neg, \neg, \neg \rangle [n]_\kappa &= k_j & \exists j \in I, n_j = n \\
\langle \neg, \neg, \neg, \Gamma_I \rangle [n]_\kappa &= k & \exists i \in I, \Gamma_i[n]_\kappa = k \\
-[-]_\tau &: \Gamma \rightarrow \tau + \perp \\
\langle \neg, \{n_i \triangleq t_i\}_I, \neg, \neg \rangle [n]_\tau &= t_j & \exists j \in I, n_j = n \\
\langle \neg, \neg, \neg, \Gamma_I \rangle [n]_\tau &= t & \exists i \in I, \Gamma_i[n]_\tau = t \\
-[-]_\sigma &: \Gamma \rightarrow \tau + \perp \\
\langle \neg, \neg, \{n_i : t_i\}_I, \neg \rangle [n]_\sigma &= t_j & \exists j \in I, n_j = n \\
\langle \neg, \neg, \neg, \Gamma_I \rangle [n]_\sigma &= t & \exists i \in I, \Gamma_i[n]_\sigma = t
\end{aligned}$$

4 Expression level

\underline{c}	$\in \mathcal{C}$	Constructor names
α	$\in \mathcal{I}$	Variable names
ϵ	$= \alpha$	Variable
	$\lambda \alpha. \epsilon$	Function
	$\zeta. \epsilon$	Method
	$\epsilon \epsilon$	Application
	let $\alpha = \epsilon$ in ϵ	Let binding
	when $(\alpha) \{ \tau_i \triangleright \epsilon_i \}_I$	Smart cast
	$\{ \tau, \epsilon \}$	Pack
	let $\{ \tau, \alpha \} = \epsilon$ in ϵ	Unpack
	Σ	Trait term
	$\epsilon.m$	Trait term Usage

With the expression trait defined by:

$$\begin{aligned}
M &= \{m_i \triangleq \epsilon_i\}_I \\
\Sigma &= \Gamma \oplus M
\end{aligned}$$

5 Illustration

5.1 Algebraic datatype

```
type Nil      = data Nil
type Cons a = data Cons (head:a) (tail:List a)
type List a = Nil | Cons a
```

Type kind

```
Nil   : ★
Cons  : ★ → ★
List  : ★ → ★
```

Type definition

```
Nil    $\triangleq$   $\underline{\text{Nil}}\{\}$ 
Cons   $\triangleq$   $\mu(\xi : \star \rightarrow \star). \Lambda(\alpha : \star). \underline{\text{Cons}}\{\text{head} : \alpha; \text{tail} : \underline{\text{Nil}}\{\} + \xi \alpha\}$ 
List   $\triangleq$   $\mu(\xi : \star \rightarrow \star). \Lambda(\alpha : \star). \underline{\text{Nil}}\{\} + \underline{\text{Cons}}\{\text{head} : \alpha; \text{tail} : \xi \alpha\}$ 
```

Function definition

```
Nil   : Nil
Cons  :  $\forall(\alpha : \star). \alpha \rightarrow \text{List } \alpha \rightarrow \text{Cons } \alpha$ 
```

5.2 Algebraic datatype ... again

```
type List a =
  data Nil
| data Cons (head:a) (tail:List a)
```

Type kind

```
List : ★ → ★
```

Type definition

```
List  $\triangleq$   $\mu(\xi : \star \rightarrow \star). \Lambda(\alpha : \star). \underline{\text{Nil}}\{\} + \underline{\text{Cons}}\{\text{head} : \alpha; \text{tail} : \xi \alpha\}$ 
```

Function definition

```
Nil   :  $\forall(\alpha : \star). \text{List } \alpha$ 
Cons  :  $\forall(\alpha : \star). \alpha \rightarrow \text{List } \alpha \rightarrow \text{List } \alpha$ 
```

5.3 Function signature

```
sig emptyList : forall a. unit -> List a
sig isEmpty   : forall a. self -> bool for List a
```

```
emptyList :  $\forall(\alpha : \star). \text{unit} \rightarrow \text{List } \alpha$ 
isEmpty   :  $\forall(\alpha : \star). \text{List } \alpha \multimap \text{bool}$ 
```

5.4 Closed trait

```
trait Access a for List a {
  sig head : self -> Option a
}
```

which is equivalent to the following type definition:

```
type Access a = trait for List a {
  sig head : self -> Option a
}
```

Type kind

Access : $\star \rightarrow \{\}$

Type definition

Access $\triangleq \Lambda(\alpha : \star). \langle \emptyset, \emptyset, \{\text{head} : \text{List } \alpha \multimap \text{Option } \alpha\}, \emptyset \rangle$

5.5 Open trait

```
trait Set a {
  sig new : self
  sig contains : self -> a -> bool
}
```

Type kind

Set : $\star \rightarrow \star$

Type definition

Set $\triangleq \Lambda(\alpha : \star). \exists(\text{self} : \star). \langle \emptyset, \emptyset, \{\text{new} : \text{self}, \text{contains} : \text{self} \multimap \alpha \rightarrow \text{bool}\}, \emptyset \rangle$

5.6 Trait with and abstract type

```
trait Pure a {
  kind t = * -> *
  sig pure : a -> t a
}
```

Type kind

Pure : $\star \rightarrow \{t : \star \rightarrow \star\}$

Type definition

Pure $\triangleq \Lambda(\alpha : \star). \exists(t : \star \rightarrow \star). \langle \emptyset, \emptyset, \{\text{pure} : \alpha \rightarrow t \alpha\}, \emptyset \rangle$

5.7 Trait with requirement

```
trait Applicative (t:type->type) with Functor t {
  sig pure : forall a.a -> t a
}
```

Applicative $\triangleq \Lambda(t : \star \rightarrow \star). \langle \emptyset, \emptyset, \{\text{pure} : \forall(\alpha : \star). \alpha \rightarrow t \alpha\}, \{\text{Functor } t\} \rangle$

5.8 Function signature with requirement

sig eq : forall a. List a -> List a -> bool with Equatable a

eq : $\langle \emptyset, \{\text{eq} \triangleq \forall(\alpha : \star). \text{List } \alpha \rightarrow \text{List } \alpha \rightarrow \text{bool}\}, \emptyset, \{\text{Equatable } \alpha\} \rangle.\text{eq}$

6 Type system

6.1 Γ and projections

$$\begin{aligned} \mathcal{K}_{\downarrow}[-] &: \Gamma \rightarrow K \\ \mathcal{K}_{\uparrow}[-] &: K \rightarrow \Gamma \\ \mathcal{T}_{\downarrow}[-] &: \Gamma \rightarrow T \\ \mathcal{T}_{\uparrow}[-] &: T \rightarrow \Gamma \\ \mathcal{S}_{\downarrow}[-] &: \Gamma \rightarrow S \\ \mathcal{S}_{\uparrow}[-] &: S \rightarrow \Gamma \\ \mathcal{W}_{\downarrow}[-] &: \Gamma \rightarrow W \end{aligned}$$

6.2 Kind inclusion

$$\frac{}{\star \subseteq_{\kappa} \star}(\text{refl}_{\star}) \quad \frac{}{K \subseteq_{\kappa} \star}(\top_{\star}) \quad \frac{k_3 \subseteq_{\kappa} k_1 \quad k_2 \subseteq_{\kappa} k_4}{k_1 \rightarrow k_2 \subseteq_{\kappa} k_3 \rightarrow k_4}(\rightarrow_{\star})$$

$$\frac{\forall j \in J, \exists i \in I, n_i = n'_j \quad k_i \subseteq_{\kappa} k'_j}{\{n_i : k_i\}_I \subseteq_{\kappa} \{n'_j : k'_j\}_J}(\text{trait}_{\star})$$

6.3 Type rules

$$\frac{\Gamma[n]_{\kappa} = k' \quad k \subseteq_{\kappa} k'}{\Gamma \vdash n :_{\kappa} k}(\text{Identity}) \quad \frac{\Gamma \vdash t_1 :_{\kappa} \star \quad \Gamma \vdash t_2 :_{\kappa} \star}{\Gamma \vdash t_1 \rightarrow t_2 :_{\kappa} \star}(\rightarrow\text{-type})$$

$$\frac{\Gamma \vdash t_1 :_{\kappa} \star \quad \Gamma \vdash t_2 :_{\kappa} \star}{\Gamma \vdash t_1 \multimap t_2 :_{\kappa} \star}(\multimap\text{-type}) \quad \frac{\Gamma \vdash t_1 :_{\kappa} \star \quad \Gamma \vdash t_2 :_{\kappa} \star}{\Gamma \vdash t_1 + t_2 :_{\kappa} \star}(+\text{-type})$$

$$\frac{\Gamma \vdash t_1 :_{\kappa} k' \rightarrow k \quad \Gamma \vdash t_2 :_{\kappa} k'}{\Gamma \vdash t_1 \ t_2 :_{\kappa} k}(\text{apply-type})$$

$$\frac{k_1 \subseteq_{\kappa} k \quad \Gamma \oplus \mathcal{K}_{\uparrow}[\{a : k\}] \vdash t :_{\kappa} k_2}{\Gamma \vdash \Lambda(a : k).t :_{\kappa} k_1 \rightarrow k_2}(\Lambda\text{-type}) \quad \frac{\Gamma \oplus \mathcal{K}_{\uparrow}[\{a : k\}] \vdash t :_{\kappa} k}{\Gamma \vdash \forall(a : k).t :_{\kappa} k}(\forall\text{-type})$$

$$\frac{\Gamma \oplus \mathcal{K}_{\uparrow}[\{a : k\}] \vdash t :_{\kappa} k}{\Gamma \vdash \exists(a : k).t :_{\kappa} k}(\exists\text{-type}) \quad \frac{\Gamma \oplus \mathcal{K}_{\uparrow}[\{a : k\}] \vdash t :_{\kappa} k}{\Gamma \vdash \mu(a : k).t :_{\kappa} k}(\mu\text{-type})$$

$$\frac{\Gamma' = \langle K, T, S, W \rangle \quad K \subseteq K' \quad \forall(n, t) \in T, \Gamma' \vdash t :_{\kappa} K[n] \quad \forall(., s) \in S, \Gamma' \vdash s :_{\kappa} \star \quad \forall w \in W, \Gamma_{\emptyset} \vdash w :_{\kappa} \{\}}{\Gamma \vdash \Gamma' :_{\kappa} K'}(\text{trait-type})$$

$$\frac{\forall i \in I, \Gamma \vdash S[m_i] : \star}{\Gamma \vdash \underline{S}_I :_{\kappa} \star}(\text{const-type})$$

$$\frac{\Gamma \vdash t_1 :_{\kappa} K' \quad \mathcal{K}_{\uparrow}[K'] \vdash n : k}{\Gamma \vdash t_1.n :_{\kappa} k}(\text{use-type-K}) \quad \frac{\Gamma \vdash t_1 :_{\kappa} \underline{C}K' \quad \mathcal{K}_{\uparrow}[K'] \vdash n : k}{\Gamma \vdash t_1.n :_{\kappa} k}(\text{use-type-C})$$

6.4 Type reduction

$$\frac{\Gamma \vdash t_1 \longrightarrow \Lambda(x : k).t_3 \quad \Gamma \vdash t_2 : k \quad \Gamma \vdash t_3[t_2/x] \longrightarrow t_4}{\Gamma \vdash t_1 \ t_2 \longrightarrow t_4}(\text{red-apply})$$

$$\frac{\Gamma[n]_\tau = t' \quad \Gamma \vdash t' \longrightarrow t''}{\Gamma \vdash n \longrightarrow t''}(\text{red-var}) \quad \frac{\Gamma \vdash t[\mu(\alpha).t/\alpha] \longrightarrow t'}{\Gamma \vdash \mu(\alpha).t \longrightarrow t'}(\text{red-}\mu)$$

$$\frac{\Gamma \vdash t_1 \longrightarrow \Gamma' \quad \Gamma' \oplus \Gamma \vdash n \longrightarrow t_2}{\Gamma \vdash t_1.n \longrightarrow t_2}(\text{red-access-var}) \quad \frac{}{\Gamma \vdash t \longrightarrow t}(\text{id})$$

6.5 Type inclusion

$$\frac{\Gamma \vdash t :_{\kappa} \star}{\Gamma \vdash t \subseteq t} (\text{sub-refl}) \quad \frac{\forall j \in J, \exists i \in I, m_i = m'_j, \Gamma \vdash t_i \subseteq t'_j}{\Gamma \vdash \underline{c}\{m_i : t_i\}_I \subseteq \underline{c}\{m'_i : t'_i\}_J} (\text{sub-const})$$

$$\frac{\Gamma \vdash t_1 \longrightarrow t_3 \quad \Gamma \vdash t_3 \subseteq t_2}{\Gamma \vdash t_1 \subseteq t_2} (\text{app-l}) \quad \frac{\Gamma \vdash t_2 \longrightarrow t_3 \quad \Gamma \vdash t_1 \subseteq t_3}{\Gamma \vdash t_1 \subseteq t_2} (\text{app-r})$$

$$\frac{\Gamma \vdash t_3 \subseteq t_1 \quad \Gamma \vdash t_2 \subseteq t_4}{\Gamma \vdash t_1 \rightarrow t_2 \subseteq t_3 \rightarrow t_4} (\text{sub-}\rightarrow) \quad \frac{\Gamma \vdash t_3 \multimap t_1 \quad \Gamma \vdash t_2 \multimap t_4}{\Gamma \vdash t_1 \multimap t_2 \subseteq t_3 \multimap t_4} (\text{sub-}\multimap)$$

$$\frac{\Gamma \vdash t_1 \subseteq t_3 \quad \Gamma \vdash t_2 \subseteq t_3}{\Gamma \vdash t_1 + t_2 \subseteq t_3} (\text{sub-}+l) \quad \frac{\Gamma \vdash t_1 \subseteq t_2}{\Gamma \vdash t_1 \subseteq t_2 + t_3} (\text{sub-}+r1)$$

$$\frac{\Gamma \vdash t_1 \subseteq t_3}{\Gamma \vdash t_1 \subseteq t_2 + t_3} (\text{sub-}+r2) \quad \frac{\Gamma \oplus \mathcal{K}_{\uparrow}[\{a : \star\}] \vdash t_1 \subseteq t_2}{\Gamma \vdash \mu(a).t_1 \subseteq \mu(a).t_2} (\text{sub-}\mu)$$

$$\frac{\Gamma \vdash t_1[\mu(a).t_1/a] \subseteq t_2}{\Gamma \vdash \mu(a).t_1 \subseteq t_2} (\text{sub-}\mu-l) \quad \frac{\Gamma \vdash t_1 \subseteq t_2[\mu(a).t_2/a]}{\Gamma \vdash t_1 \subseteq \mu(a).t_2} (\text{sub-}\mu-r)$$

$$\frac{k' \subseteq_{\kappa} k \quad \Gamma \oplus \mathcal{K}_{\uparrow}[\{x : k\}] \vdash t_1 \subseteq t_2}{\Gamma \vdash \Lambda(x : k).t_1 \subseteq \Lambda(x : k').t_2} (\text{sub-}\Lambda)$$

$$\frac{k \subseteq_{\kappa} k' \quad \Gamma \oplus \mathcal{K}_{\uparrow}[\{x : k\}] \vdash t_1 \subseteq t_2}{\Gamma \vdash \forall(x : k).t_1 \subseteq \forall(x : k').t_2} (\text{sub-}\forall)$$

$$\frac{k \subseteq_{\kappa} k' \quad \Gamma \oplus \mathcal{K}_{\uparrow}[\{x : k\}] \vdash t_1 \subseteq t_2}{\Gamma \vdash \exists(x : k).t_1 \subseteq \exists(x : k').t_2} (\text{sub-}\exists)$$

$$\frac{\begin{array}{l} \mathcal{K}_{\downarrow}[\Gamma_1] \subseteq \mathcal{K}_{\downarrow}[\Gamma_2] \\ \forall(n, t) \in \mathcal{T}_{\downarrow}[\Gamma_2], \exists(n', t') \in \mathcal{T}_{\downarrow}[\Gamma_1], n = n', \Gamma \vdash t' \subseteq t \\ \forall(n, t) \in \mathcal{S}_{\downarrow}[\Gamma_2], \exists(n', t') \in \mathcal{S}_{\downarrow}[\Gamma_1], n = n', \Gamma \vdash t' \subseteq t \end{array}}{\Gamma \vdash \Gamma_1 \subseteq \Gamma_2} (\text{sub-trait})$$

6.6 Expression rules

$$\frac{\Gamma[e]_\sigma = t' \quad \Gamma \vdash t' \subseteq t}{\Gamma \vdash e : t}(\text{id}) \quad \frac{\Gamma \vdash n : t_1 \rightarrow t_2 \quad \Gamma \vdash a : t_3 \quad \Gamma \vdash t_3 \subseteq t_1}{\Gamma \vdash n \ a : t_2}(\text{app})$$

$$\frac{\Gamma \vdash n : t_1 \multimap t_2 \quad \Gamma \vdash a : t_3 \quad \Gamma \vdash t_3 \subseteq t_1}{\Gamma \vdash a \ n : t_2}(\text{call})$$

$$\frac{\Gamma \oplus \mathcal{S}_\uparrow[\{n : t_1\}] \vdash a : t_2}{\Gamma \vdash \lambda n. a : t_1 \rightarrow t_2}(\text{abstr}) \quad \frac{\Gamma \oplus \mathcal{S}_\uparrow[\{\mathbf{self} : t_1\}] \vdash a : t_2}{\Gamma \vdash \zeta. a : t_1 \multimap t_2}(\text{meth})$$

$$\frac{\Gamma \vdash r : \underline{c}S \quad \mathcal{S}_\uparrow[S] \oplus \Gamma \vdash n : t}{\Gamma \vdash r.n : t}(\text{access}) \quad \frac{\Gamma \vdash r : \Gamma' \quad \Gamma' \oplus \Gamma \vdash n : t}{\Gamma \vdash r.n : t}(\text{use})$$

$$\frac{\Gamma \vdash e : \forall(a : k). t_1 \quad \Gamma \vdash t_2 :_\kappa k}{\Gamma \vdash e : t_1[t_2/a]}(\forall\text{-elim}) \quad \frac{\mathcal{K}_\uparrow[\{a : k\}] \oplus \Gamma \vdash e : t}{\Gamma \vdash e : \forall(a : k). t}(\forall\text{-intro})$$

$$\frac{\Gamma \vdash e_1 : \exists(a : k). t_1 \quad \mathcal{K}_\uparrow[\{A : k\}] \oplus \mathcal{S}_\uparrow[\{a : t_1\}] \oplus \Gamma \vdash e_2 : t_2 \quad A \notin \mathbf{ftv}(t_2)}{\Gamma \vdash \mathbf{let} \{A, a\} = e_1 \ \mathbf{in} \ e_2 : t_2}(\exists\text{-elim})$$

$$\frac{\Gamma \vdash t_1 :_\kappa k \quad \Gamma \vdash e : t_2[t_1/a]}{\Gamma \vdash \{t_1, e\} : \exists(a : k). t_2}(\exists\text{-intro}) \quad \frac{\Gamma \vdash e_1 : t_1 \quad \Gamma \oplus \mathcal{T}_\uparrow[\{a : t_1\}] \vdash e_2 : t_2}{\Gamma \vdash \mathbf{let} \ a = e_1 \ \mathbf{in} \ e_2 : t_2}(\text{let-in})$$

$$\frac{\Gamma \vdash a : \biguplus_I t_i \quad \forall i \in I, \mathcal{S}_\uparrow[\{a : t_i\}] \oplus \Gamma \vdash e_i : t}{\Gamma \vdash \mathbf{when}(a)\{t_i \triangleright e_i\}_I : t}(\text{when})$$

$$\frac{\Gamma \vdash \Gamma_1 \subseteq \Gamma_2 \quad \Gamma_1[m_i]_\sigma = t_i \quad \forall i \in I, \Gamma_1 \oplus \Gamma \vdash e_i : t_i}{\Gamma \vdash \Gamma_1 \otimes \{m_i \triangleq e_i\}_I : \Gamma_2}(\text{trait})$$
