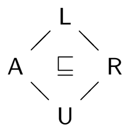
1 Syntax

Constant Qualifiers	$\mathfrak{q}$	$\in$	$\mathit{Quals} = \{\mathsf{U}, \mathsf{R}, \mathsf{A}, \mathsf{L}\}$



Qualifiers	q	$::=$	$\xi \mid \mathfrak{q}$
Locations	$\mathfrak{l}$	$\in$	Locs
Constant Region Identifiers	$\mathfrak{r}$	$\in$	RIds
Region Identifiers	r	$::=$	$\varrho \mid \mathfrak{r}$
Expressions	e	$::=$	$\mathfrak{l} \mid$
			$x \mid {}^{q_a}\lambda x{:}\tau.\, e \mid e_1\, e_2 \mid$
			${}^{q_a}\langle\rangle \mid \mathtt{let}\ \langle\rangle = e_1\ \mathtt{in}\ e_2 \mid {}^{q_a}\langle e_1, e_2\rangle \mid \mathtt{let}\ \langle x_1, x_2\rangle = e_1\ \mathtt{in}\ e_2 \mid$
			${}^{q_a}(\!\|\!) \mid {}^{q_a}(\!\| e_1, e_2 \|\!) \mid \mathtt{fst}\, e \mid \mathtt{snd}\, e \mid$
			$\mathtt{abort}\, e \mid {}^{q_a}\mathtt{inl}\, e \mid {}^{q_a}\mathtt{inr}\, e \mid \mathtt{case}\ e_1\ \mathtt{of}\ \mathtt{inl}\, x \Rightarrow e_l \parallel \mathtt{inr}\, y \Rightarrow e_r \mid$
			${}^{q_a}\Lambda\xi.\, e \mid e\,[q] \mid {}^{q_a}\mathtt{pack}(q, e) \mid \mathtt{let}\ \mathtt{pack}(\xi, x) = e_1\ \mathtt{in}\ e_2 \mid$
			${}^{q_a}\Lambda\overline{\alpha}.\, e \mid e\,[\overline{\tau}] \mid {}^{q_a}\mathtt{pack}(\overline{\tau}, e) \mid \mathtt{let}\ \mathtt{pack}(\overline{\alpha}, x) = e_1\ \mathtt{in}\ e_2 \mid$
			${}^{q_a}\Lambda\alpha.\, e \mid e\,[\tau] \mid {}^{q_a}\mathtt{pack}(\tau, e) \mid \mathtt{let}\ \mathtt{pack}(\alpha, x) = e_1\ \mathtt{in}\ e_2 \mid$
			${}^{q_a}\mathtt{fold}\, e \mid \mathtt{unfold}\, e \mid$
			${}^{q_c, q_h}\mathtt{newrgn} \mid \mathtt{freergn}\, e_1\, e_2 \mid$
			${}^{q_a}\mathtt{new}\, e_1\, e_2\, e_3 \mid \mathtt{free}\, e_1\, e_2 \mid \mathtt{read}\, e_1\, e_2 \mid \mathtt{swap}\, e_1\, e_2\, e_3 \mid$
			${}^{q_a}\Lambda\varrho.\, e \mid e\,[r] \mid {}^{q_a}\mathtt{pack}(r, e) \mid \mathtt{let}\ \mathtt{pack}(\varrho, x) = e_1\ \mathtt{in}\ e_2$
Pointers	$\mathfrak{p}$	$\in$	Ptrs
Values	v	$::=$	$\lambda x{:}\tau.\, e \mid$
			$\langle\rangle \mid \langle \mathfrak{l}_1, \mathfrak{l}_2\rangle \mid$
			$(\!\|\!) \mid (\!\| e_1, e_2 \|\!) \mid$
			$\mathtt{inl}\, \mathfrak{l} \mid \mathtt{inr}\, \mathfrak{l} \mid$
			$\Lambda\xi.\, e \mid \mathtt{pack}(q, e) \mid \Lambda\overline{\alpha}.\, e \mid \mathtt{pack}(\overline{\tau}, e) \mid \Lambda\alpha.\, e \mid \mathtt{pack}(\tau, e) \mid$
			$\mathtt{fold}\, \mathfrak{l} \mid$
			$\mathtt{cap} \mid \mathtt{hnd}\, \mathfrak{r} \mid \mathtt{ref}\, \mathfrak{r}\, \mathfrak{p} \mid$
			$\Lambda\varrho.\, e \mid \mathtt{pack}(r, e)$
PreTypes	$\overline{\tau}$	$::=$	$\overline{\alpha} \mid$
			$\tau_1 \multimap \tau_2 \mid$
			$\mathbf{1}_{\otimes} \mid \tau_1 \otimes \tau_2 \mid$
			$\mathbf{1}_{\circledast} \mid \tau_1 \circledast \tau_2 \mid$
			$\mathbf{0} \mid \tau_1 \oplus \tau_2 \mid$
			$\forall\xi.\tau \mid \exists\xi.\tau \mid \forall\overline{\alpha}.\tau \mid \exists\overline{\alpha}.\tau \mid \forall\alpha.\tau \mid \exists\alpha.\tau \mid$
			$\mu\overline{\alpha}.\tau \mid$
			$\mathsf{cap}\, r \mid \mathsf{hnd}\, r \mid \mathsf{ref}\, r\, \tau \mid$
			$\forall\varrho.\tau \mid \exists\varrho.\tau$
Types	τ	$::=$	$\alpha \mid {}^{q}\overline{\tau}$
Type-level Contexts	Δ	$::=$	$\bullet \mid \Delta, \xi \mid \Delta, \overline{\alpha} \mid \Delta, \alpha \mid \Delta, \varrho$
Expression-level Contexts	Γ	$::=$	$\bullet \mid \Gamma, x{:}\tau$
Flags	$\mathfrak{f}$	$\in$	$\{\mathsf{unused}, \mathsf{used}\}$
Stores	σ	$::=$	$\bullet \mid \sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathfrak{f})$
Store Typings	Σ	$::=$	$\bullet \mid \Sigma, \mathfrak{l} \mapsto \tau$
Regions	θ	$::=$	$\bullet \mid \theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l})$
Region Typings	Θ	$::=$	$\bullet \mid \Theta, \mathfrak{p} \mapsto (\mathfrak{q}, \tau)$
Region Marks	υ	$::=$	${}^{\mathfrak{q}}\mathtt{live} \mid \mathsf{dead}$
Region Capability Tokens	Υ	$::=$	${}^{\mathfrak{q}}\mathsf{pre} \mid \mathsf{abs}$
Heaps	ψ	$::=$	$\bullet \mid \psi, \mathfrak{r} \mapsto (\upsilon, \theta)$
Heap Typings	Ψ	$::=$	$\bullet \mid \Psi, \mathfrak{r} \mapsto (\Upsilon, \Theta)$

2 Dynamic Semantics

2.1 $(\sigma; \mathfrak{q}; v) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')$

$$\frac{\mathfrak{l} \notin dom(\sigma)}{(\sigma; \mathfrak{q}; v) \xrightarrow{\mathsf{alloc}} (\sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathsf{unused}); \mathfrak{l})}$$

2.2 $(\sigma; \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}'; v')$

$$\frac{\mathfrak{q} \sqsubseteq \mathsf{R}}{(\sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathfrak{f}); \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathsf{used}); \mathfrak{q}; v)} \qquad \frac{\mathsf{A} \sqsubseteq \mathfrak{q}}{(\sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathfrak{f}); \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma; \mathfrak{q}; v)}$$

$$\frac{\mathfrak{l} \neq \mathfrak{l}' \qquad (\sigma_1; \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma_2; \mathfrak{q}; v)}{(\sigma_1, \mathfrak{l}' \mapsto (\mathfrak{q}', v', \mathfrak{f}'); \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma_2, \mathfrak{l}' \mapsto (\mathfrak{q}', v', \mathfrak{f}'); \mathfrak{q}; v)}$$

2.3 $(\psi; \mathfrak{q}_r) \xrightarrow{\mathsf{newrgn}} (\psi'; \mathfrak{r}')$

$$\frac{\mathfrak{r} \notin dom(\psi)}{\psi \xrightarrow{\mathsf{newrgn}} (\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \bullet); \mathfrak{r})}$$

2.4 $(\psi; \mathfrak{r}) \xrightarrow{\mathsf{freergn}} \psi'$

$$\frac{}{(\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta); \mathfrak{r}) \xrightarrow{\mathsf{freergn}} \psi, \mathfrak{r} \mapsto (\texttt{dead}, \theta)} \qquad \frac{\mathfrak{r} \neq \mathfrak{r}' \qquad (\psi_1; \mathfrak{r}) \xrightarrow{\mathsf{freergn}} \psi_2}{(\psi_1, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{r}) \xrightarrow{\mathsf{freergn}} \psi_2, \mathfrak{r}' \mapsto (\upsilon', \theta')}$$

2.5 $(\theta; \mathfrak{q}; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\theta'; \mathfrak{p}')$ and $(\psi; \mathfrak{r}; \mathfrak{q}; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\psi'; \mathfrak{p}')$

$$\frac{\mathfrak{p} \notin dom(\theta)}{(\theta; \mathfrak{q}; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l}_r); \mathfrak{p})}$$

$$\frac{(\theta; \mathfrak{q}; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\theta'; \mathfrak{p}')}{(\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta); \mathfrak{r}; \mathfrak{q}; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta'); \mathfrak{p}')} \qquad \frac{\mathfrak{r} \neq \mathfrak{r}' \qquad (\psi_1; \mathfrak{r}; \mathfrak{q}; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\psi_2; \mathfrak{p})}{(\psi_1, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{r}; \mathfrak{q}; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\psi_2, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{p})}$$

2.6 $(\theta; \mathfrak{p}) \xrightarrow{\mathsf{free}} (\theta'; \mathfrak{l}'_r)$ and $(\psi; \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{free}} (\psi'; \mathfrak{l}'_r)$

$$\frac{}{(\theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l}_r); \mathfrak{p}) \xrightarrow{\mathsf{free}} (\theta; \mathfrak{l}_r)} \qquad \frac{\mathfrak{p} \neq \mathfrak{p}' \qquad (\theta_1; \mathfrak{p}) \xrightarrow{\mathsf{free}} (\theta_2; \mathfrak{l}_r)}{(\theta_1, \mathfrak{p}' \mapsto (\mathfrak{q}', \mathfrak{l}'_r); \mathfrak{p}) \xrightarrow{\mathsf{free}} (\theta_2, \mathfrak{p}' \mapsto (\mathfrak{q}', \mathfrak{l}'_r); \mathfrak{l}_r)}$$

$$\frac{(\theta; \mathfrak{p}) \xrightarrow{\mathsf{free}} (\theta'; \mathfrak{l}'_r)}{(\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta); \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{free}} (\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta'); \mathfrak{l}'_r)} \qquad \frac{\mathfrak{r} \neq \mathfrak{r}' \qquad (\psi_1; \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{free}} (\psi_2; \mathfrak{l}_r)}{(\psi_1, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{free}} (\psi_2, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{l}_r)}$$

2.7 $(\theta; \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}'_r$ and $(\psi; \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}'_r$

$$\frac{}{(\theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l}_r); \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}_r} \qquad \frac{\mathfrak{p} \neq \mathfrak{p}' \qquad (\theta_1; \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}_r}{(\theta_1, \mathfrak{p}' \mapsto (\mathfrak{q}', \mathfrak{l}'_r); \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}_r}$$

$$\frac{(\theta; \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}'_r}{(\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta); \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}'_r} \qquad \frac{\mathfrak{r} \neq \mathfrak{r}' \qquad (\psi_1; \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}_r}{(\psi_1, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{r}; \mathfrak{p}) \xrightarrow{\mathsf{read}} \mathfrak{l}_r}$$

2.8 $(\theta; \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\theta'; \mathfrak{l}'_r)$ and $(\psi; \mathfrak{r}; \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\psi'; \mathfrak{l}_r{}')$

$$\frac{}{(\theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l}_r); \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l}_{r\star}); \mathfrak{l}_r)} \qquad \frac{\mathfrak{p} \neq \mathfrak{p}' \qquad (\theta_1; \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\theta_2; \mathfrak{l}_r)}{(\theta_1, \mathfrak{p}' \mapsto (\mathfrak{q}', \mathfrak{l}'_r); \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\theta_2, \mathfrak{p}' \mapsto (\mathfrak{q}', \mathfrak{l}'_r); \mathfrak{l}_r)}$$

$$\frac{(\theta; \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\theta'; \mathfrak{l}'_r)}{(\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta); \mathfrak{r}; \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\psi, \mathfrak{r} \mapsto ({}^{\mathfrak{q}_r}\texttt{live}, \theta'); \mathfrak{l}'_r)} \qquad \frac{\mathfrak{r} \neq \mathfrak{r}' \qquad (\psi_1; \mathfrak{r}; \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\psi_2; \mathfrak{l}_r)}{(\psi_1, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{r}; \mathfrak{p}; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\psi_2, \mathfrak{r}' \mapsto (\upsilon', \theta'); \mathfrak{l}_r)}$$

2.9 $(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')$

$$\frac{(\sigma; \mathfrak{q}_a; \lambda x{:}\tau.\, e) \xrightarrow{\textsf{alloc}} (\sigma'; \mathfrak{l})}{(\sigma, \psi, {}^{\mathfrak{q}_a} \lambda x{:}\tau.\, e) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi', e_1\, e_2) \longmapsto (\sigma', \psi', e_1'\, e_2)} \qquad \frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e_2')}{(\sigma, \psi, \mathfrak{l}_1\, e_2) \longmapsto (\sigma', \psi', \mathfrak{l}_1\, e_2')} \qquad \frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\textsf{fetch}} (\sigma'; \mathfrak{q}_a; \lambda x{:}\tau.\, e)}{(\sigma, \psi, \mathfrak{l}_1\, \mathfrak{l}_2) \longmapsto (\sigma', \psi, e[\mathfrak{l}_2/x])}$$

$$\frac{(\sigma; \mathfrak{q}_a; \langle\rangle) \xrightarrow{\textsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a} \langle\rangle) \longmapsto (\sigma', \psi', \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, \texttt{let}\ \langle\rangle = e_1\ \texttt{in}\ e_2) \longmapsto (\sigma', \psi', \texttt{let}\ \langle\rangle = e_1'\ \texttt{in}\ e_2)} \qquad \frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\textsf{fetch}} (\sigma'; \mathfrak{q}_a; \langle\rangle)}{(\sigma, \psi, \texttt{let}\ \langle\rangle = \mathfrak{l}_1\ \texttt{in}\ e_2) \longmapsto (\sigma', \psi, e_2)}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, {}^{\mathfrak{q}_a} \langle e_1, e_2\rangle) \longmapsto (\sigma', \psi', {}^{\mathfrak{q}_a} \langle e_1', e_2\rangle)} \qquad \frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e_2')}{(\sigma, \psi, {}^{\mathfrak{q}_a} \langle \mathfrak{l}_1, e_2\rangle) \longmapsto (\sigma', \psi', {}^{\mathfrak{q}_a} \langle \mathfrak{l}_1, e_2'\rangle)} \qquad \frac{(\sigma; \mathfrak{q}_a; \langle \mathfrak{l}_1, \mathfrak{l}_2\rangle) \xrightarrow{\textsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a} \langle \mathfrak{l}_1, \mathfrak{l}_2\rangle) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, \texttt{let}\ \langle x, y\rangle = e_1\ \texttt{in}\ e_2) \longmapsto (\sigma', \psi', \texttt{let}\ \langle x, y\rangle = e_1'\ \texttt{in}\ e_2)}$$

$$\frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\textsf{fetch}} (\sigma'; \mathfrak{q}_a; \langle \mathfrak{l}_x, \mathfrak{l}_y\rangle)}{(\sigma, \psi, \texttt{let}\ \langle x, y\rangle = \mathfrak{l}_1\ \texttt{in}\ e_2) \longmapsto (\sigma', \psi, e_2[\mathfrak{l}_x/x][\mathfrak{l}_y/y])}$$

$$\frac{(\sigma; \mathfrak{q}_a; (\!|\,|\!)) \xrightarrow{\textsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a} (\!|\,|\!)) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma; \mathfrak{q}_a; (\!| e_1, e_2 |\!)) \xrightarrow{\textsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a} (\!| e_1, e_2 |\!)) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, \texttt{fst}\, e) \longmapsto (\sigma', \psi', \texttt{fst}\, e')} \qquad \frac{(\sigma; \mathfrak{l}) \xrightarrow{\textsf{fetch}} (\sigma'; \mathfrak{q}_a; (\!| e_1, e_2 |\!))}{(\sigma, \psi, \texttt{fst}\, \mathfrak{l}) \longmapsto (\sigma', \psi, e_1)}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, \texttt{snd}\, e) \longmapsto (\sigma', \psi', \texttt{snd}\, e')} \qquad \frac{(\sigma; \mathfrak{l}) \xrightarrow{\textsf{fetch}} (\sigma'; \mathfrak{q}_a; (\!| e_1, e_2 |\!))}{(\sigma, \psi, \texttt{snd}\, \mathfrak{l}) \longmapsto (\sigma', \psi, e_2)}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, \texttt{abort}\, e) \longmapsto (\sigma', \psi', \texttt{abort}\, e')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, {}^{q_a}\texttt{inl}\, e_1) \longmapsto (\sigma', \psi', {}^{q_a}\texttt{inl}\, e_1')} \qquad \frac{(\sigma; \mathfrak{q}_a; \texttt{inl}\, \mathfrak{l}_1) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\texttt{inl}\, \mathfrak{l}_1) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e_2')}{(\sigma, \psi, {}^{q_a}\texttt{inr}\, e_2) \longmapsto (\sigma', \psi', {}^{q_a}\texttt{inr}\, e_2')} \qquad \frac{(\sigma; \mathfrak{q}_a; \texttt{inr}\, \mathfrak{l}_2) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\texttt{inr}\, \mathfrak{l}_2) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, \texttt{case}\ e_1\ \texttt{of}\ \texttt{inl}\, x \Rightarrow e_l \parallel \texttt{inr}\, y \Rightarrow e_r) \longmapsto (\sigma', \psi', \texttt{case}\ e_1'\ \texttt{of}\ \texttt{inl}\, x \Rightarrow e_l \parallel \texttt{inr}\, y \Rightarrow e_r)}$$

$$\frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \texttt{inl}\, \mathfrak{l}_x)}{(\sigma, \psi, \texttt{case}\ \mathfrak{l}_1\ \texttt{of}\ \texttt{inl}\, x \Rightarrow e_l \parallel \texttt{inr}\, y \Rightarrow e_r) \longmapsto (\sigma', \psi, e_l[\mathfrak{l}_x/x])}$$

$$\frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \texttt{inr}\, \mathfrak{l}_y)}{(\sigma, \psi, \texttt{case}\ \mathfrak{l}_1\ \texttt{of}\ \texttt{inl}\, x \Rightarrow e_l \parallel \texttt{inr}\, y \Rightarrow e_r) \longmapsto (\sigma', \psi, e_r[\mathfrak{l}_y/y])}$$

$$\frac{(\sigma; \mathfrak{q}_a; \Lambda\xi.\, e) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\Lambda\xi.\, e) \longmapsto (\sigma', \psi, \mathfrak{l}')} \qquad \frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, e\,[q]) \longmapsto (\sigma', \psi', e'\,[q])} \qquad \frac{(\sigma; \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \Lambda\xi.\, e)}{(\sigma, \psi', \mathfrak{l}\,[q]) \longmapsto (\sigma', \psi, e[q/\xi])}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, {}^{q_a}\mathtt{pack}(q, e)) \longmapsto (\sigma', \psi', {}^{q_a}\mathtt{pack}(q, e'))} \qquad \frac{(\sigma; \mathfrak{q}_a; \mathtt{pack}(q, l)) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\mathtt{pack}(q, l)) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, \mathtt{let\ pack}(\xi, x) = e_1 \mathtt{\ in\ } e_2) \longmapsto (\sigma', \psi', \mathtt{let\ pack}(\xi, x) = e_1' \mathtt{\ in\ } e_2)}$$

$$\frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \mathtt{pack}(q, \mathfrak{l}_x))}{(\sigma, \psi, \mathtt{let\ pack}(\xi, x) = \mathfrak{l}_1 \mathtt{\ in\ } e_2) \longmapsto (\sigma', \psi, e_2[q/\xi][\mathfrak{l}_x/x])}$$

$$\frac{(\sigma; \mathfrak{q}_a; \Lambda\overline{\alpha}.\, e) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\Lambda\overline{\alpha}.\, e) \longmapsto (\sigma', \psi', \mathfrak{l}')} \qquad \frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, e\,[\overline{\tau}]) \longmapsto (\sigma', \psi', e'\,[\overline{\tau}])} \qquad \frac{(\sigma; \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \Lambda\overline{\alpha}.\, e)}{(\sigma, \psi, \mathfrak{l}\,[\overline{\tau}]) \longmapsto (\sigma', \psi, e[\overline{\tau}/\overline{\alpha}])}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, {}^{q_a}\mathtt{pack}(\overline{\tau}, e)) \longmapsto (\sigma', \psi', {}^{q_a}\mathtt{pack}(\overline{\tau}, e'))} \qquad \frac{(\sigma; \mathfrak{q}_a; \mathtt{pack}(\overline{\tau}, \mathfrak{l})) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\mathtt{pack}(\overline{\tau}, \mathfrak{l})) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, \mathtt{let\ pack}(\overline{\alpha}, x) = e_1 \mathtt{\ in\ } e_2) \longmapsto (\sigma', \psi', \mathtt{let\ pack}(\overline{\alpha}, x) = e_1' \mathtt{\ in\ } e_2)}$$

$$\frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \mathtt{pack}(\overline{\tau}, \mathfrak{l}_x))}{(\sigma, \psi, \mathtt{let\ pack}(\overline{\alpha}, x) = \mathfrak{l}_1 \mathtt{\ in\ } e_2) \longmapsto (\sigma', \psi, e_2[\overline{\tau}/\overline{\alpha}][\mathfrak{l}_x/x])}$$

$$\frac{(\sigma; \mathfrak{q}_a; \Lambda\alpha.\, e) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\Lambda\alpha.\, e) \longmapsto (\sigma', \psi, \mathfrak{l}')} \qquad \frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, e\,[\tau]) \longmapsto (\sigma', \psi', e'\,[\tau])} \qquad \frac{(\sigma; \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \Lambda\alpha.\, e)}{(\sigma, \psi, \mathfrak{l}\,[\tau]) \longmapsto (\sigma', \psi, e[\tau/\alpha])}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, {}^{q_a}\mathtt{pack}(\tau, e)) \longmapsto (\sigma', \psi', {}^{q_a}\mathtt{pack}(\tau, e'))} \qquad \frac{(\sigma; \mathfrak{q}_a; \mathtt{pack}(\tau, \mathfrak{l})) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\mathtt{pack}(\tau, l)) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, \mathtt{let\ pack}(\alpha, x) = e_1 \mathtt{\ in\ } e_2) \longmapsto (\sigma', \psi', \mathtt{let\ pack}(\alpha, x) = e_1' \mathtt{\ in\ } e_2)}$$

$$\frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \mathtt{pack}(\tau, \mathfrak{l}_x))}{(\sigma, \psi, \mathtt{let\ pack}(\alpha, x) = \mathfrak{l}_1 \mathtt{\ in\ } e_2) \longmapsto (\sigma', \psi, e_2[\tau/\alpha][\mathfrak{l}_x/x])}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, {}^{q_a}\mathtt{fold}\, e) \longmapsto (\sigma', \psi', {}^{q_a}\mathtt{fold}\, e')} \qquad \frac{(\sigma; \mathfrak{q}_a; \mathtt{fold}\, \mathfrak{l}) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\mathtt{fold}\, \mathfrak{l}) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, \mathtt{unfold}\, e) \longmapsto (\sigma', \psi', \mathtt{unfold}\, e')} \qquad \frac{(\sigma; \mathfrak{l}) \xrightarrow{\mathsf{fetch}} (\sigma'; \mathfrak{q}_a; \mathtt{fold}\, \mathfrak{l}')}{(\sigma, \psi, \mathtt{unfold}\, \mathfrak{l}) \longmapsto (\sigma', \psi', \mathfrak{l}')}$$

$$\frac{\begin{array}{c}(\psi; \mathfrak{q}_c) \xrightarrow{\mathsf{newrgn}} (\psi'; \mathfrak{r}') \qquad (\sigma; \mathfrak{q}_c; \texttt{cap}) \xrightarrow{\mathsf{alloc}} (\sigma'_c; \mathfrak{l}'_c) \\ (\sigma'_c; \mathfrak{q}_h; \texttt{hnd}\,\mathfrak{r}') \xrightarrow{\mathsf{alloc}} (\sigma'_h; \mathfrak{l}'_h) \qquad (\sigma'_h; \mathsf{L}; \langle \mathfrak{l}_c, \mathfrak{l}_h \rangle) \xrightarrow{\mathsf{alloc}} (\sigma'_z; \mathfrak{l}'_z) \qquad (\sigma'_z; \mathsf{L}; \texttt{pack}(\mathfrak{r}', \mathfrak{l}'_z)) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')\end{array}}{(\sigma, \psi, {}^{\mathfrak{q}_c, \mathfrak{q}_h}\texttt{newrgn}) \longmapsto (\sigma', \psi', \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e'_1)}{(\sigma, \psi, \texttt{freergn}\, e_1\, e_2) \longmapsto (\sigma', \psi', \texttt{freergn}\, e'_1\, e_2)} \qquad \frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e'_2)}{(\sigma, \psi, \texttt{freergn}\, \mathfrak{l}_1\, e_2) \longmapsto (\sigma', \psi', \texttt{freergn}\, \mathfrak{l}_1\, e'_2)}$$

$$\frac{(\sigma; \mathfrak{l}_c) \xrightarrow{\mathsf{fetch}} (\sigma_c; \mathfrak{q}_c; \texttt{cap}) \qquad (\sigma_c; \mathfrak{l}_h) \xrightarrow{\mathsf{fetch}} (\sigma_h; \mathfrak{q}_h; \texttt{hnd}\,\mathfrak{r}') \qquad (\psi; \mathfrak{r}') \xrightarrow{\mathsf{freergn}} \psi' \qquad (\sigma_h; \mathsf{L}; \langle\rangle) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, \texttt{freergn}\, \mathfrak{l}_c\, \mathfrak{l}_h) \longmapsto (\sigma', \psi', \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e'_1)}{(\sigma, \psi, {}^{q_a}\texttt{new}\, e_1\, e_2\, e_3) \longmapsto (\sigma', \psi', {}^{q_a}\texttt{new}\, e'_1\, e_2\, e_3)} \qquad \frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e'_2)}{(\sigma, \psi, {}^{q_a}\texttt{new}\, \mathfrak{l}_1\, e_2\, e_3) \longmapsto (\sigma', \psi', {}^{q_a}\texttt{new}\, \mathfrak{l}_1\, e'_2\, e_3)}$$

$$\frac{(\sigma, \psi, e_3) \longmapsto (\sigma', \psi', e'_3)}{(\sigma, \psi, {}^{q_a}\texttt{new}\, \mathfrak{l}_1\, \mathfrak{l}_2\, e_3) \longmapsto (\sigma', \psi', {}^{q_a}\texttt{new}\, \mathfrak{l}_1\, \mathfrak{l}_2\, e'_3)}$$

$$\frac{\begin{array}{c}(\sigma; \mathfrak{l}_c) \xrightarrow{\mathsf{fetch}} (\sigma_c; \mathfrak{q}_c; \texttt{cap}) \qquad (\sigma_c; \mathfrak{l}_h) \xrightarrow{\mathsf{fetch}} (\sigma_h; \mathfrak{q}_h; \texttt{hnd}\,\mathfrak{r}') \\ (\psi; \mathfrak{r}'; \mathfrak{q}_a; \mathfrak{l}_r) \xrightarrow{\mathsf{new}} (\psi'; \mathfrak{p}') \\ (\sigma_h; \mathfrak{q}_c; \texttt{cap}) \xrightarrow{\mathsf{alloc}} (\sigma'_c; \mathfrak{l}'_c) \qquad (\sigma'_c; \mathfrak{q}_a; \texttt{ref}\,\mathfrak{r}'\,\mathfrak{p}') \xrightarrow{\mathsf{alloc}} (\sigma'_p; \mathfrak{l}'_p) \qquad (\sigma'_p; \mathsf{L}; \langle \mathfrak{l}'_c, \mathfrak{l}'_p \rangle) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')\end{array}}{(\sigma, \psi, {}^{q_a}\texttt{new}\, \mathfrak{l}_c\, \mathfrak{l}_h\, \mathfrak{l}_r) \longmapsto (\sigma', \psi', l')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e'_1)}{(\sigma, \psi, \texttt{free}\, e_1\, e_2) \longmapsto (\sigma', \psi', \texttt{free}\, e'_1\, e_2)} \qquad \frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e'_2)}{(\sigma, \psi, \texttt{free}\, \mathfrak{l}_1\, e_2) \longmapsto (\sigma', \psi', \texttt{free}\, \mathfrak{l}_1\, e'_2)}$$

$$\frac{\begin{array}{c}(\sigma; \mathfrak{l}_c) \xrightarrow{\mathsf{fetch}} (\sigma_c; \mathfrak{q}_c; \texttt{cap}) \qquad (\sigma_c; \mathfrak{l}_p) \xrightarrow{\mathsf{fetch}} (\sigma_p; \mathfrak{q}_p; \texttt{ref}\,\mathfrak{r}'\,\mathfrak{p}') \\ (\psi; \mathfrak{r}'; \mathfrak{p}') \xrightarrow{\mathsf{free}} (\psi'; \mathfrak{l}'_r) \qquad (\sigma_p; \mathfrak{q}_c; \texttt{cap}) \xrightarrow{\mathsf{alloc}} (\sigma'_c; \mathfrak{l}'_c) \qquad (\sigma'_c; \mathsf{L}; \langle \mathfrak{l}'_c, \mathfrak{l}'_r \rangle) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')\end{array}}{(\sigma, \psi, \texttt{free}\, \mathfrak{l}_c\, \mathfrak{l}_p) \longmapsto (\sigma', \psi', \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e'_1)}{(\sigma, \psi, \texttt{read}\, e_1\, e_2) \longmapsto (\sigma', \psi', \texttt{read}\, e'_1\, e_2)} \qquad \frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e'_2)}{(\sigma, \psi, \texttt{read}\, \mathfrak{l}_1\, e_2) \longmapsto (\sigma', \psi', \texttt{read}\, \mathfrak{l}_1\, e'_2)}$$

$$\frac{\begin{array}{c}(\sigma; \mathfrak{l}_c) \xrightarrow{\mathsf{fetch}} (\sigma_c; \mathfrak{q}_c; \texttt{cap}) \qquad (\sigma_c; \mathfrak{l}_p) \xrightarrow{\mathsf{fetch}} (\sigma_p; \mathfrak{q}_p; \texttt{ref}\,\mathfrak{r}'\,\mathfrak{p}') \\ (\psi; \mathfrak{r}'; \mathfrak{p}') \xrightarrow{\mathsf{read}} \mathfrak{l}'_r \qquad (\sigma_p; \mathfrak{q}_c; \texttt{cap}) \xrightarrow{\mathsf{alloc}} (\sigma'_c; \mathfrak{l}'_c) \\ (\sigma'_c; \mathfrak{q}_p; \texttt{ref}\,\mathfrak{r}'\,\mathfrak{p}') \xrightarrow{\mathsf{alloc}} (\sigma'_p; \mathfrak{l}'_p) \qquad (\sigma'_p; \mathsf{L}; \langle \mathfrak{l}'_c, \mathfrak{l}'_p \rangle) \xrightarrow{\mathsf{alloc}} (\sigma'_z; \mathfrak{l}'_z) \qquad (\sigma'_z; \mathsf{L}; \langle \mathfrak{l}'_z, \mathfrak{l}'_r \rangle) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')\end{array}}{(\sigma, \psi, \texttt{read}\, \mathfrak{l}_c\, \mathfrak{l}_p) \longmapsto (\sigma', \psi', \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e'_1)}{(\sigma, \psi, \texttt{swap}\, e_1\, e_2\, e_3) \longmapsto (\sigma', \psi', \texttt{swap}\, e'_1\, e_2\, e_3)} \qquad \frac{(\sigma, \psi, e_2) \longmapsto (\sigma', \psi', e'_2)}{(\sigma, \psi, \texttt{swap}\, \mathfrak{l}_1\, e_2\, e_3) \longmapsto (\sigma', \psi', \texttt{swap}\, \mathfrak{l}_1\, e'_2\, e_3)}$$

$$\frac{(\sigma, \psi, e_3) \longmapsto (\sigma', \psi', e'_3)}{(\sigma, \psi, \texttt{swap}\, \mathfrak{l}_1\, \mathfrak{l}_2\, e_3) \longmapsto (\sigma', \psi', \texttt{swap}\, \mathfrak{l}_1\, \mathfrak{l}_2\, e'_3)}$$

$$\frac{\begin{array}{c}(\sigma; \mathfrak{l}_c) \xrightarrow{\mathsf{fetch}} (\sigma_c; \mathfrak{q}_c; \texttt{cap}) \qquad (\sigma_c; \mathfrak{l}_p) \xrightarrow{\mathsf{fetch}} (\sigma_p; \mathfrak{q}_p; \texttt{ref}\,\mathfrak{r}'\,\mathfrak{p}') \\ (\psi; \mathfrak{r}'; \mathfrak{p}'; \mathfrak{l}_{r\star}) \xrightarrow{\mathsf{swap}} (\psi'; \mathfrak{l}'_r) \qquad (\sigma_p; \mathfrak{q}_c; \texttt{cap}) \xrightarrow{\mathsf{alloc}} (\sigma'_c; \mathfrak{l}'_c) \\ (\sigma'_c; \mathfrak{q}_p; \texttt{ref}\,\mathfrak{r}'\,\mathfrak{p}') \xrightarrow{\mathsf{alloc}} (\sigma'_p; \mathfrak{l}'_p) \qquad (\sigma'_p; \mathsf{L}; \langle \mathfrak{l}'_c, \mathfrak{l}'_p \rangle) \xrightarrow{\mathsf{alloc}} (\sigma'_z; \mathfrak{l}'_z) \qquad (\sigma'_z; \mathsf{L}; \langle \mathfrak{l}'_z, \mathfrak{l}'_r \rangle) \xrightarrow{\mathsf{alloc}} (\sigma'; \mathfrak{l}')\end{array}}{(\sigma, \psi, \texttt{swap}\, \mathfrak{l}_c\, \mathfrak{l}_p\, \mathfrak{l}_{r\star}) \longmapsto (\sigma', \psi', \mathfrak{l}')}$$

$$\frac{(\sigma; \mathfrak{q}_a; \Lambda\varrho.\, e) \xrightarrow{\textsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\Lambda\varrho.\, e) \longmapsto (\sigma', \psi, \mathfrak{l}')} \qquad \frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, e\,[r]) \longmapsto (\sigma', \psi', e'\,[r])} \qquad \frac{(\sigma; \mathfrak{l}) \xrightarrow{\textsf{fetch}} (\sigma'; \mathfrak{q}_a; \Lambda\varrho.\, e)}{(\sigma, \psi', l\,[r]) \longmapsto (\sigma', \psi, e[r/\varrho])}$$

$$\frac{(\sigma, \psi, e) \longmapsto (\sigma', \psi', e')}{(\sigma, \psi, {}^{q_a}\texttt{pack}(r, e)) \longmapsto (\sigma', \psi', {}^{q_a}\texttt{pack}(r, e'))} \qquad \frac{(\sigma; \mathfrak{q}_a; \texttt{pack}(r, l)) \xrightarrow{\textsf{alloc}} (\sigma'; \mathfrak{l}')}{(\sigma, \psi, {}^{\mathfrak{q}_a}\texttt{pack}(r, l)) \longmapsto (\sigma', \psi, \mathfrak{l}')}$$

$$\frac{(\sigma, \psi, e_1) \longmapsto (\sigma', \psi', e_1')}{(\sigma, \psi, \texttt{let pack}(\varrho, x) = e_1 \texttt{ in } e_2) \longmapsto (\sigma', \psi', \texttt{let pack}(\varrho, x) = e_1' \texttt{ in } e_2)}$$

$$\frac{(\sigma; \mathfrak{l}_1) \xrightarrow{\textsf{fetch}} (\sigma'; \mathfrak{q}_a; \texttt{pack}(r, \mathfrak{l}_x))}{(\sigma, \psi, \texttt{let pack}(\varrho, x) = \mathfrak{l}_1 \texttt{ in } e_2) \longmapsto (\sigma', \psi, e_2[r/\varrho][\mathfrak{l}_x/x])}$$

2.10 $(\sigma, \psi, e) \longmapsto^* (\sigma', \psi', e')$

$$\frac{}{(\sigma, \psi, e) \longmapsto^* (\sigma, \psi, e)} \qquad \frac{(\sigma_1, \psi_1, e_1) \longmapsto^* (\sigma_2, \psi_2, e_2) \qquad (\sigma_2, \psi_2, e_2) \longmapsto^* (\sigma_3, \psi_3, e_3)}{(\sigma_1, \psi_1, e_1) \longmapsto^* (\sigma_3, \psi_3, e_3)}$$

$$\frac{(\sigma_1, \psi_1, e_1) \longmapsto (\sigma_2, \psi_2, e_2)}{(\sigma_1, \psi_1, e_1) \longmapsto^* (\sigma_2, \psi_2, e_2)}$$

3 Static Semantics

3.1 $\Delta \vdash q \preceq q'$

$$\frac{FV(q) \subseteq \Delta}{\Delta \vdash \mathsf{U} \preceq q} \qquad \frac{\mathsf{q}_1 \sqsubseteq \mathsf{q}_2}{\Delta \vdash \mathsf{q}_1 \preceq \mathsf{q}_2} \qquad \frac{FV(q) \subseteq \Delta}{\Delta \vdash q \preceq \mathsf{L}}$$

$$\frac{FV(q) \subseteq \Delta}{\Delta \vdash q \preceq q} \qquad \frac{\Delta \vdash q_1 \preceq q_2 \qquad \Delta \vdash q_2 \preceq q_3}{\Delta \vdash q_1 \preceq q_3}$$

3.2 $\Delta \vdash \tau \preceq q'$

$$\frac{FV(\tau) \subseteq \Delta}{\Delta \vdash \tau \preceq \mathsf{L}} \qquad \frac{\Delta \vdash q \preceq q' \qquad FV(\overline{\tau}) \subseteq \Delta}{\Delta \vdash {}^{q}\overline{\tau} \preceq q'}$$

3.3 $\Delta \vdash \Gamma \preceq q'$

$$\frac{FV(q') \subseteq \Delta}{\Delta \vdash \bullet \preceq q'} \qquad \frac{\Delta \vdash \Gamma \preceq q' \qquad \Delta \vdash \tau \preceq q'}{\Delta \vdash \Gamma, x{:}\tau \preceq q'}$$

3.4 $\Delta \vdash \Sigma \preceq q'$

$$\frac{FV(q') \subseteq \Delta}{\Delta \vdash \bullet \preceq q'} \qquad \frac{\Delta \vdash \Sigma \preceq q' \qquad \Delta \vdash \tau \preceq q'}{\Delta \vdash \Sigma, \mathfrak{l} \mapsto \tau \preceq q'}$$

3.5 $\vdash \Theta \preceq \mathsf{q}'$

$$\frac{}{\vdash \bullet \preceq \mathsf{q}'} \qquad \frac{\vdash \Theta \preceq \mathsf{q}' \qquad \vdash \mathsf{q} \preceq \mathsf{q}'}{\vdash \Theta, \mathfrak{p} \mapsto (\mathsf{q}, \tau) \preceq \mathsf{q}'}$$

3.6 $\vdash \Upsilon \preceq \mathsf{q}'$

$$\frac{\bullet \vdash \mathsf{q} \preceq \mathsf{q}'}{\vdash {}^{\mathsf{q}}\mathsf{pre} \preceq \mathsf{q}'} \qquad \frac{}{\vdash \mathsf{abs} \preceq \mathsf{q}'}$$

3.7 $\vdash \Psi \preceq \mathsf{q}'$

$$\frac{}{\vdash \bullet \preceq \mathsf{q}'} \qquad \frac{\vdash \Psi \preceq \mathsf{q}' \qquad \vdash \Upsilon \preceq \mathsf{q}' \qquad \vdash \Theta \preceq \mathsf{q}'}{\vdash \Psi, \mathfrak{r} \mapsto (\Upsilon, \Theta) \preceq \mathsf{q}'}$$

3.8 $\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \leadsto \Gamma$

$$\frac{}{\Delta \vdash \bullet \boxdot \bullet \leadsto \bullet}$$

$$\frac{\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \leadsto \Gamma}{\Delta \vdash \Gamma_1, x{:}\tau \boxdot \Gamma_2 \leadsto \Gamma, x{:}\tau} \qquad \frac{\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \leadsto \Gamma}{\Delta \vdash \Gamma_1 \boxdot \Gamma_2, x{:}\tau \leadsto \Gamma, x{:}\tau}$$

$$\frac{\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \leadsto \Gamma \qquad \Delta \vdash \tau \preceq \mathsf{R}}{\Delta \vdash \Gamma_1, x{:}\tau \boxdot \Gamma_2, x{:}\tau \leadsto \Gamma, x{:}\tau}$$

3.9 $\Delta \vdash \Sigma_1 \odot \Sigma_2 \leadsto \Sigma$

$$\frac{}{\Delta \vdash \bullet \odot \bullet \leadsto \bullet}$$

$$\frac{\Delta \vdash \Sigma_1 \odot \Sigma_2 \leadsto \Sigma}{\Delta \vdash \Sigma_1, \mathfrak{l} \mapsto \tau \odot \Sigma_2 \leadsto \Sigma, \mathfrak{l} \mapsto \tau} \qquad \frac{\Delta \vdash \Sigma_1 \odot \Sigma_2 \leadsto \Sigma}{\Delta \vdash \Sigma_1 \odot \Sigma_2, \mathfrak{l} \mapsto \tau \leadsto \Sigma, \mathfrak{l} \mapsto \tau}$$

$$\frac{\Delta \vdash \Sigma_1 \odot \Sigma_2 \leadsto \Sigma \qquad \Delta \vdash \tau \preceq \mathsf{R}}{\Delta \vdash \Sigma_1, \mathfrak{l} \mapsto \tau \odot \Sigma_2, \mathfrak{l} \mapsto \tau \leadsto \Sigma, \mathfrak{l} \mapsto \tau}$$

3.10 $\vdash \Upsilon_1 \odot \Upsilon_2 \leadsto \Upsilon$

$$\frac{\mathfrak{q} \sqsubseteq \mathsf{R}}{\vdash {}^{\mathfrak{q}}\mathsf{pre} \odot {}^{\mathfrak{q}}\mathsf{pre} \leadsto {}^{\mathfrak{q}}\mathsf{pre}} \qquad \frac{}{\vdash {}^{\mathfrak{q}}\mathsf{pre} \odot \mathsf{abs} \leadsto {}^{\mathfrak{q}}\mathsf{pre}} \qquad \frac{}{\vdash \mathsf{abs} \odot {}^{\mathfrak{q}}\mathsf{pre} \leadsto {}^{\mathfrak{q}}\mathsf{pre}} \qquad \frac{}{\vdash \mathsf{abs} \odot \mathsf{abs} \leadsto \mathsf{abs}}$$

3.11 $\vdash \Theta_1 \odot \Theta_2 \leadsto \Theta$

$$\frac{}{\vdash \bullet \odot \bullet \leadsto \bullet}$$

$$\frac{\vdash \Theta_1 \odot \Theta_2 \leadsto \Theta}{\vdash \Theta_1, \mathfrak{p} \mapsto (\mathfrak{q}, \tau) \odot \Theta_2 \leadsto \Theta, \mathfrak{p} \mapsto (\mathfrak{q}, \tau)} \qquad \frac{\vdash \Theta_1 \odot \Theta_2 \leadsto \Theta}{\vdash \Theta_1 \odot \Theta_2, \mathfrak{p} \mapsto (\mathfrak{q}, \tau) \leadsto \Theta, \mathfrak{p} \mapsto (\mathfrak{q}, \tau)}$$

$$\frac{\vdash \Theta_1 \odot \Theta_2 \leadsto \Theta \qquad \mathfrak{q} \sqsubseteq \mathsf{R}}{\vdash \Theta_1, \mathfrak{p} \mapsto (\mathfrak{q}, \tau) \odot \Theta_2, \mathfrak{p} \mapsto (\mathfrak{q}, \tau) \leadsto \Theta, \mathfrak{p} \mapsto (\mathfrak{q}, \tau)}$$

3.12 $\vdash \Psi_1 \odot \Psi_2 \leadsto \Psi$

$$\frac{}{\vdash \bullet \odot \bullet \leadsto \bullet}$$

$$\frac{\vdash \Psi_1 \odot \Psi_2 \leadsto \Psi}{\vdash \Psi_1, \mathfrak{r} \mapsto (\Upsilon, \Theta) \odot \Psi_2 \leadsto \Psi, \mathfrak{r} \mapsto (\Upsilon, \Theta)} \qquad \frac{\vdash \Psi_1 \odot \Psi_2 \leadsto \Psi}{\vdash \Psi_1 \odot \Psi_2, \mathfrak{r} \mapsto (\Upsilon, \Theta) \leadsto \Psi, \mathfrak{r} \mapsto (\Upsilon, \Theta)}$$

$$\frac{\vdash \Psi_1 \odot \Psi_2 \leadsto \Psi \qquad \vdash \Upsilon_1 \odot \Upsilon_2 \leadsto \Upsilon \qquad \vdash \Theta_1 \odot \Theta_2 \leadsto \Theta}{\vdash \Psi_1, \mathfrak{r} \mapsto (\Upsilon_1, \Theta_1) \odot \Psi_2, \mathfrak{r} \mapsto (\Upsilon_2, \Theta_2) \leadsto \Psi, \mathfrak{r} \mapsto (\Upsilon, \Theta)}$$

3.13 $\Delta; \Sigma \vdash \mathfrak{l} : \tau$

$$\frac{FV(\tau) \subseteq \Delta}{\Delta; \bullet, \mathfrak{l} \mapsto \tau \vdash \mathfrak{l} : \tau}$$

3.14 $\Delta; \Gamma \vdash x : \tau$

$$\frac{FV(\tau) \subseteq \Delta}{\Delta; \bullet, x{:}\tau \vdash x : \tau}$$

3.15 $\Delta; \Gamma; \Sigma \vdash e : \tau$

$$\frac{\Delta; \Sigma \vdash \mathfrak{l} : \tau}{\Delta; \bullet; \Sigma \vdash \mathfrak{l} : \tau} \qquad \frac{\Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \qquad \Delta \vdash \Sigma_1 \preceq \mathsf{A} \qquad \Delta; \Gamma; \Sigma_2 \vdash e : \tau}{\Delta; \Gamma; \Sigma \vdash e : \tau}$$

$$\frac{\Delta; \Gamma \vdash x : \tau}{\Delta; \Gamma; \bullet \vdash x : \tau} \qquad \frac{\Delta; \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta; \Gamma_1 \preceq \mathsf{A} \qquad \Delta; \Gamma_2; \Sigma \vdash e : \tau}{\Delta; \Gamma; \Sigma \vdash e : \tau}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma \preceq q_a \qquad \Delta \vdash \Sigma \preceq q_a \\ \Delta; \Gamma, x{:}\tau_x; \Sigma \vdash e : \tau\end{array}}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\lambda x{:}\tau_x.\, e : {}^{q_a}(\tau_x \multimap \tau)} \qquad \frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}(\tau_x \multimap \tau) \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : \tau_x\end{array}}{\Delta; \Gamma; \Sigma \vdash e_1\, e_2 : \tau}$$

$$\frac{FV(q_a) \subseteq \Delta}{\Delta; \bullet; \bullet \vdash {}^{q_a}\langle\rangle : {}^{q_a}\mathbf{1}_{\otimes}} \qquad \frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}\mathbf{1}_{\otimes} \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : \tau\end{array}}{\Delta; \Gamma; \Sigma \vdash \texttt{let}\ \langle\rangle = e_1\ \texttt{in}\ e_2 : \tau}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : \tau_1 \qquad \Delta \vdash \tau_1 \preceq q_a \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : \tau_2 \qquad \Delta \vdash \tau_2 \preceq q_a\end{array}}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\langle e_1, e_2\rangle : {}^{q_a}(\tau_1 \otimes \tau_2)}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}(\tau_x \otimes \tau_y) \qquad \Delta; \Gamma_2, x{:}\tau_x, y{:}\tau_y; \Sigma_2 \vdash e_2 : \tau\end{array}}{\Delta; \Gamma; \Sigma \vdash \texttt{let}\ \langle x, y\rangle = e_1\ \texttt{in}\ e_2 : \tau}$$

$$\frac{\Delta \vdash \Gamma \preceq q_a \qquad \Delta \vdash \Sigma \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\llparenthesis\rrparenthesis : {}^{q_a}\mathbf{1}_{\circledast}}$$

$$\frac{\Delta \vdash \Gamma \preceq q_a \qquad \Delta \vdash \Sigma \preceq q_a \qquad \Delta; \Gamma; \Sigma \vdash e_1 : \tau_1 \qquad \Delta; \Gamma; \Sigma \vdash e_2 : \tau_2}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\llparenthesis e_1, e_2\rrparenthesis : {}^{q_a}(\tau_1 \circledast \tau_2)}$$

$$\frac{\Delta; \Gamma; \Sigma \vdash e : {}^{q_a}(\tau_1 \circledast \tau_2)}{\Delta; \Gamma; \Sigma \vdash \texttt{fst}\, e : \tau_1} \qquad \frac{\Delta; \Gamma; \Sigma \vdash e : {}^{q_a}(\tau_1 \circledast \tau_2)}{\Delta; \Gamma; \Sigma \vdash \texttt{snd}\, e : \tau_2}$$

$$\frac{\Delta; \Gamma; \Sigma \vdash e : {}^{q_a}\mathbf{0}}{\Delta; \Gamma; \Sigma \vdash \texttt{abort}\, e : \tau}$$

$$\frac{\Delta; \Gamma; \Sigma \vdash e_1 : \tau_1 \qquad \Delta \vdash \tau_1 \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\texttt{inl}\, e_1 : {}^{q_a}(\tau_1 \oplus \tau_2)} \qquad \frac{\Delta; \Gamma; \Sigma \vdash e_2 : \tau_2 \qquad \Delta \vdash \tau_2 \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\texttt{inl}\, e_2 : {}^{q_a}(\tau_1 \oplus \tau_2)}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}(\tau_1 \oplus \tau_2) \\ \Delta; \Gamma_2, x{:}\tau_1 \vdash e_l \vdash \tau \qquad \Delta; \Gamma_2, y{:}\tau_2 \vdash e_r \vdash \tau\end{array}}{\Delta; \Gamma; \Sigma \vdash \texttt{case}\ e_1\ \texttt{of}\ \texttt{inl}\, x \Rightarrow e_l \parallel \texttt{inr}\, y \Rightarrow e_r : \tau}$$

$$\dfrac{\Delta \vdash \Gamma \preceq q_a \qquad \Delta \vdash \Sigma \preceq q_a \qquad \Delta, \xi; \Gamma; \Sigma \vdash e : \tau}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\Lambda\xi.\, e : {}^{q_a}(\forall \xi.\tau)} \qquad \dfrac{\Delta; \Gamma; \Sigma \vdash e_1 : {}^{q_a}(\forall \xi.\tau)}{\Delta; \Gamma; \Sigma \vdash e_1\,[q_2] : \tau[q_2/\xi]}$$

$$\dfrac{\Delta; \Gamma; \Sigma \vdash e_2 : \tau[q_1/\xi] \qquad \Delta \vdash \tau[q_1/\xi] \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\texttt{pack}(q_1, e_2) : {}^{q_a}(\exists \xi.\tau)} \qquad \dfrac{\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \qquad \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}(\exists \xi.\tau) \qquad \Delta, \xi; \Gamma_2, x{:}\tau; \Sigma_2 \vdash e_2 : \tau' \qquad FV(\tau') \subseteq \Delta}{\Delta; \Gamma; \Sigma \vdash \texttt{let pack}(\xi, x) = e_1 \texttt{ in } e_2 : \tau'}$$

$$\dfrac{\Delta \vdash \Gamma \preceq q_a \qquad \Delta \vdash \Sigma \preceq q_a \qquad \Delta, \overline{\alpha}; \Gamma; \Sigma \vdash e : \tau}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\Lambda\overline{\alpha}.\, e : {}^{q_a}(\forall \overline{\alpha}.\tau)} \qquad \dfrac{\Delta; \Gamma; \Sigma \vdash e_1 : {}^{q_a}(\forall \overline{\alpha}.\tau)}{\Delta; \Gamma; \Sigma \vdash e_1\,[\overline{\tau_2}] : \tau[\overline{\tau_2}/\overline{\alpha}]}$$

$$\dfrac{\Delta; \Gamma; \Sigma \vdash e_2 : \tau[\overline{\tau_1}/\overline{\alpha}] \qquad \Delta \vdash \tau[\overline{\tau_1}/\overline{\alpha}] \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\texttt{pack}(\overline{\tau_1}, e_2) : {}^{q_a}(\exists \overline{\alpha}.\tau)} \qquad \dfrac{\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \qquad \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}(\exists \overline{\alpha}.\tau) \qquad \Delta, \overline{\alpha}; \Gamma_2, x{:}\tau; \Sigma_2 \vdash e_2 : \tau' \qquad FV(\tau') \subseteq \Delta}{\Delta; \Gamma; \Sigma \vdash \texttt{let pack}(\overline{\alpha}, x) = e_1 \texttt{ in } e_2 : \tau'}$$

$$\dfrac{\Delta \vdash \Gamma \preceq q_a \qquad \Delta \vdash \Sigma \preceq q_a \qquad \Delta, \alpha; \Gamma; \Sigma \vdash e : \tau}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\Lambda\alpha.\, e : {}^{q_a}(\forall \alpha.\tau)} \qquad \dfrac{\Delta; \Gamma; \Sigma \vdash e_1 : {}^{q_a}(\forall \alpha.\tau)}{\Delta; \Gamma; \Sigma \vdash e_1\,[\tau_2] : \tau[\tau_2/\alpha]}$$

$$\dfrac{\Delta; \Gamma; \Sigma \vdash e_2 : \tau[\tau_1/\alpha] \qquad \Delta \vdash \tau[\tau_1/\alpha] \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\texttt{pack}(\tau_1, e_2) : {}^{q_a}(\exists \alpha.\tau)} \qquad \dfrac{\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \qquad \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}(\exists \alpha.\tau) \qquad \Delta, \alpha; \Gamma_2, x{:}\tau; \Sigma_2 \vdash e_2 : \tau' \qquad FV(\tau') \subseteq \Delta}{\Delta; \Gamma; \Sigma \vdash \texttt{let pack}(\alpha, x) = e_1 \texttt{ in } e_2 : \tau'}$$

$$\dfrac{\Delta; \Gamma; \Sigma \vdash e : \tau[\mu\overline{\alpha}.\tau/\overline{\alpha}] \qquad \Delta \vdash \tau[\mu\overline{\alpha}.\tau/\overline{\alpha}] \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\texttt{fold}\, e : {}^{q_a}(\mu\overline{\alpha}.\tau)} \qquad \dfrac{\Delta; \Gamma; \Sigma \vdash e : {}^{q_a}(\mu\overline{\alpha}.\tau)}{\Delta; \Gamma; \Sigma \vdash \texttt{unfold}\, e : \tau[\mu\overline{\alpha}.\tau/\overline{\alpha}]}$$

$$\frac{}{\Delta; \bullet; \bullet \vdash {}^{q_c, q_h}\mathtt{newrgn} : {}^{\mathsf{L}}(\exists \varrho. {}^{\mathsf{L}}({}^{q_c}(\mathsf{cap}\, \varrho) \otimes {}^{q_h}(\mathsf{hnd}\, \varrho)))}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_c}(\mathsf{cap}\, r) \qquad \Delta \vdash \mathsf{A} \preceq q_c \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : {}^{q_h}(\mathsf{hnd}\, r)\end{array}}{\Delta; \Gamma; \Sigma \vdash \mathtt{freergn}\, e_1\, e_2 : {}^{\mathsf{L}}\mathbf{1}_{\otimes}}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \boxdot \Gamma_3 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \odot \Sigma_3 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_c}(\mathsf{cap}\, r) \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : {}^{q_h}(\mathsf{hnd}\, r) \qquad \Delta; \Gamma_3; \Sigma_3 \vdash e_3 : \tau \qquad \Delta \vdash \tau \preceq \mathsf{A}\end{array}}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\mathtt{new}\, e_1\, e_2\, e_3 : {}^{\mathsf{L}}({}^{q_c}(\mathsf{cap}\, r) \otimes {}^{q_a}(\mathsf{ref}\, r\, \tau))}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \boxdot \Gamma_3 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \odot \Sigma_3 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_c}(\mathsf{cap}\, r) \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : {}^{q_h}(\mathsf{hnd}\, r) \qquad \Delta \vdash \mathsf{R} \preceq q_a \qquad \Delta; \Gamma_3; \Sigma_3 \vdash e_3 : \tau\end{array}}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\mathtt{new}\, e_1\, e_2\, e_3 : {}^{\mathsf{L}}({}^{q_c}(\mathsf{cap}\, r) \otimes {}^{q_a}(\mathsf{ref}\, r\, \tau))}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_c}(\mathsf{cap}\, r) \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : {}^{q_a}(\mathsf{ref}\, r\, \tau) \qquad \Delta \vdash \mathsf{A} \preceq q_a\end{array}}{\Delta; \Gamma; \Sigma \vdash \mathtt{free}\, e_1\, e_2 : {}^{\mathsf{L}}({}^{q_c}(\mathsf{cap}\, r) \otimes \tau)}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_c}(\mathsf{cap}\, r) \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : {}^{q_a}(\mathsf{ref}\, r\, \tau) \qquad \Delta \vdash \tau \preceq \mathsf{R}\end{array}}{\Delta; \Gamma; \Sigma \vdash \mathtt{read}\, e_1\, e_2 : {}^{\mathsf{L}}({}^{\mathsf{L}}({}^{q_c}(\mathsf{cap}\, r) \otimes {}^{q_a}(\mathsf{ref}\, r\, \tau)) \otimes \tau)}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \boxdot \Gamma_3 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \odot \Sigma_3 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_c}(\mathsf{cap}\, r) \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : {}^{q_a}(\mathsf{ref}\, r\, \tau_2) \qquad \Delta; \Gamma_3; \Sigma_3 \vdash e_3 : \tau_3\end{array}}{\Delta; \Gamma; \Sigma \vdash \mathtt{swap}\, e_1\, e_2\, e_3 : {}^{\mathsf{L}}({}^{\mathsf{L}}({}^{q_c}(\mathsf{cap}\, r) \otimes {}^{q_a}(\mathsf{ref}\, r\, \tau_3)) \otimes \tau_2)}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \boxdot \Gamma_3 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \odot \Sigma_3 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_c}(\mathsf{cap}\, r) \qquad \Delta; \Gamma_2; \Sigma_2 \vdash e_2 : {}^{q_a}(\mathsf{ref}\, r\, \tau) \qquad \Delta; \Gamma_3; \Sigma_3 \vdash e_3 : \tau\end{array}}{\Delta; \Gamma; \Sigma \vdash \mathtt{swap}\, e_1\, e_2\, e_3 : {}^{\mathsf{L}}({}^{\mathsf{L}}({}^{q_c}(\mathsf{cap}\, r) \otimes {}^{q_a}(\mathsf{ref}\, r\, \tau)) \otimes \tau)}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma \preceq q_a \qquad \Delta \vdash \Sigma \preceq q_a \\ \Delta, \alpha; \Gamma; \Sigma \vdash e : \tau\end{array}}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\Lambda\varrho.\, e : {}^{q_a}(\forall \varrho. \tau)}$$

$$\frac{\Delta; \Gamma; \Sigma \vdash e_1 : {}^{q_a}(\forall \varrho. \tau)}{\Delta; \Gamma; \Sigma \vdash e_1\, [r_2] : \tau[r_2/\varrho]}$$

$$\frac{\Delta; \Gamma; \Sigma \vdash e_2 : \tau[r_1/\varrho] \qquad \Delta \vdash \tau[r_1/\varrho] \preceq q_a}{\Delta; \Gamma; \Sigma \vdash {}^{q_a}\mathtt{pack}(r_1, e_2) : {}^{q_a}(\exists \varrho. \tau)}$$

$$\frac{\begin{array}{c}\Delta \vdash \Gamma_1 \boxdot \Gamma_2 \rightsquigarrow \Gamma \qquad \Delta \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \\ \Delta; \Gamma_1; \Sigma_1 \vdash e_1 : {}^{q_a}(\exists \varrho. \tau) \\ \Delta, \varrho; \Gamma_2, x{:}\tau; \Sigma_2 \vdash e_2 : \tau' \qquad FV(\tau') \subseteq \Delta\end{array}}{\Delta; \Gamma; \Sigma \vdash \mathtt{let\ pack}(\varrho, x) = e_1\ \mathtt{in}\ e_2 : \tau'}$$

3.16 $\Psi \vdash_{\mathsf{cap}} \mathfrak{r} : \mathfrak{q}$

$$\frac{}{\bullet, \mathfrak{r} \mapsto ({}^{\mathfrak{q}}\mathsf{pre}, \bullet) \vdash_{\mathsf{cap}} \mathfrak{r} : \mathfrak{q}}$$

3.17 $\Psi \vdash_{\mathsf{hnd}} \mathfrak{r}$

$$\frac{}{\bullet, \mathfrak{r} \mapsto (\mathsf{abs}, \bullet) \vdash_{\mathsf{hnd}} \mathfrak{r}}$$

3.18 $\Psi \vdash_{\mathsf{ref}} (\mathfrak{r}, \mathfrak{p}) : (\mathfrak{q}, \tau)$

$$\frac{}{\bullet, \mathfrak{r} \mapsto (\mathsf{abs}, \bullet, \mathfrak{p} \mapsto (\mathfrak{q}, \tau)) \vdash_{\mathsf{ref}} (\mathfrak{r}, \mathfrak{p}) : (\mathfrak{q}, \tau)}$$

3.19 $\Sigma; \Psi \vdash (\mathfrak{q}, v) : \tau$

$$\frac{\bullet \vdash \Sigma \preceq \mathfrak{q} \qquad \bullet; \bullet, x{:}\tau_x; \Sigma \vdash e : \tau}{\Sigma; \bullet \vdash (\mathfrak{q}, \lambda x{:}\tau_x.\, e) : {}^{\mathfrak{q}}(\tau_x \multimap \tau)}$$

$$\frac{}{\bullet; \bullet \vdash (\mathfrak{q}, \langle\rangle) : {}^{\mathfrak{q}}\mathbf{1}_{\otimes}} \qquad \frac{\bullet \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \qquad \bullet; \Sigma_1 \vdash \mathfrak{l}_1 : \tau_1 \qquad \bullet \vdash \tau_1 \preceq \mathfrak{q} \bullet; \Sigma_2 \vdash \mathfrak{l}_2 : \tau_2 \qquad \bullet \vdash \tau_2 \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \langle \mathfrak{l}_1, \mathfrak{l}_2 \rangle) : {}^{\mathfrak{q}}(\tau_1 \otimes \tau_2)}$$

$$\frac{\bullet \vdash \Sigma \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, (\!|\!|\!)) : {}^{\mathfrak{q}}\mathbf{1}_{\circledast}} \qquad \frac{\bullet \vdash \Sigma \preceq \mathfrak{q} \qquad \bullet; \bullet; \Sigma \vdash e_1 : \tau_1 \qquad \bullet; \bullet; \Sigma \vdash e_2 : \tau_2}{\Sigma; \bullet \vdash (\mathfrak{q}, (\!| e_1, e_2 |\!)) : {}^{\mathfrak{q}}(\tau_1 \circledast \tau_2)}$$

$$\frac{\bullet; \Sigma \vdash \mathfrak{l} : \tau_1 \qquad \bullet \vdash \tau_1 \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \mathtt{inl}\, \mathfrak{l}) : {}^{\mathfrak{q}}(\tau_1 \oplus \tau_2)} \qquad \frac{\bullet; \Sigma \vdash \mathfrak{l} : \tau_2 \qquad \bullet \vdash \tau_2 \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \mathtt{inr}\, \mathfrak{l}) : {}^{\mathfrak{q}}(\tau_1 \oplus \tau_2)}$$

$$\frac{\begin{array}{c}\bullet \vdash \Sigma \preceq \mathfrak{q} \\ \bullet, \xi; \bullet; \Sigma \vdash e : \tau\end{array}}{\Sigma; \bullet \vdash (\mathfrak{q}, \Lambda\xi.\, e) : {}^{\mathfrak{q}}(\forall\xi.\tau)} \qquad \frac{\bullet; \Sigma \vdash \mathfrak{l}_2 : \tau[q_1/\xi] \qquad \bullet \vdash \tau[q_1/\xi] \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \mathtt{pack}(q_1, \mathfrak{l}_2)) : {}^{\mathfrak{q}}(\exists\xi.\tau)}$$

$$\frac{\begin{array}{c}\bullet \vdash \Sigma \preceq \mathfrak{q} \\ \bullet, \overline{\alpha}; \bullet; \Sigma \vdash e : \tau\end{array}}{\Sigma; \bullet \vdash (\mathfrak{q}, \Lambda\overline{\alpha}.\, e) : {}^{\mathfrak{q}}(\forall\overline{\alpha}.\tau)} \qquad \frac{\bullet; \Sigma \vdash \mathfrak{l}_2 : \tau[\overline{\tau_1}/\overline{\alpha}] \qquad \bullet \vdash \tau[\overline{\tau_1}/\overline{\alpha}] \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \mathtt{pack}(\overline{\tau_1}, \mathfrak{l}_2)) : {}^{\mathfrak{q}}(\exists\overline{\alpha}.\tau)}$$

$$\frac{\begin{array}{c}\bullet \vdash \Sigma \preceq \mathfrak{q} \\ \bullet, \alpha; \bullet; \Sigma \vdash e : \tau\end{array}}{\Sigma; \bullet \vdash (\mathfrak{q}, \Lambda\alpha.\, e) : {}^{\mathfrak{q}}(\forall\alpha.\tau)} \qquad \frac{\bullet; \Sigma \vdash \mathfrak{l}_2 : \tau[\tau_1/\alpha] \qquad \bullet \vdash \tau[\tau_1/\alpha] \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \mathtt{pack}(\tau_1, \mathfrak{l}_2)) : {}^{\mathfrak{q}}(\exists\alpha.\tau)}$$

$$\frac{\bullet; \Sigma \vdash \mathfrak{l} : \tau[\mu\overline{\alpha}.\tau/\overline{\alpha}] \qquad \bullet \vdash \tau[\mu\overline{\alpha}.\tau/\overline{\alpha}] \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \mathtt{fold}\, \mathfrak{l}) : {}^{\mathfrak{q}}(\mu\overline{\alpha}.\tau)}$$

$$\frac{\Psi \vdash_{\mathsf{cap}} \mathfrak{r} : \mathfrak{q}}{\bullet; \Psi \vdash (\mathfrak{q}, \mathsf{cap}) : {}^{\mathfrak{q}}(\mathsf{cap}\, \mathfrak{r})} \qquad \frac{\Psi \vdash_{\mathsf{hnd}} \mathfrak{r}}{\bullet; \Psi \vdash (\mathfrak{q}, \mathtt{hnd}\, \mathfrak{r}) : {}^{\mathfrak{q}}(\mathsf{hnd}\, \mathfrak{r})} \qquad \frac{\Psi \vdash_{\mathsf{ref}} (\mathfrak{r}, \mathfrak{p}) : (\mathfrak{q}, \tau)}{\bullet; \Psi \vdash (\mathfrak{q}, \mathtt{ref}\, \mathfrak{r}\, \mathfrak{p}) : {}^{\mathfrak{q}}(\mathsf{ref}\, \mathfrak{r}\, \tau)}$$

$$\frac{\begin{array}{c}\bullet \vdash \Sigma \preceq \mathfrak{q} \\ \bullet, \varrho; \bullet; \Sigma \vdash e : \tau\end{array}}{\Sigma; \bullet \vdash (\mathfrak{q}, \Lambda\varrho.\, e) : {}^{\mathfrak{q}}(\forall\varrho.\tau)} \qquad \frac{\bullet; \Sigma \vdash \mathfrak{l}_2 : \tau[r_1/\varrho] \qquad \bullet \vdash \tau[r_1/\varrho] \preceq \mathfrak{q}}{\Sigma; \bullet \vdash (\mathfrak{q}, \mathtt{pack}(r_1, \mathfrak{l}_2)) : {}^{\mathfrak{q}}(\exists\varrho.\tau)}$$

3.20 $\vdash \Psi$ skel

$$\frac{}{\vdash \bullet\ \mathsf{skel}} \qquad \frac{\vdash \Psi\ \mathsf{skel}}{\vdash \Psi, \mathfrak{r} \mapsto (\mathsf{abs}, \bullet)\ \mathsf{skel}}$$

3.21 $\Psi \vdash \sigma : \Sigma$

$$\frac{\vdash \Psi\ \mathsf{skel}}{\Psi \vdash \bullet : \bullet} \qquad \frac{\Sigma_v; \Psi_v \vdash (\mathfrak{q}, v) : \tau \qquad \bullet \vdash \Sigma_v \odot \Sigma \rightsquigarrow \Sigma_\star \qquad \Psi_\star \vdash \sigma : \Sigma_\star \qquad \vdash \Psi_\star \odot \Psi_v \rightsquigarrow \Psi}{\Psi \vdash \sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathfrak{f}) : \Sigma, \mathfrak{l} \mapsto \tau}$$

$$\frac{\Psi \vdash \sigma : \Sigma \qquad \mathfrak{q} \sqsubseteq \mathsf{R}}{\Psi \vdash \sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathsf{used}) : \Sigma} \qquad \frac{\Psi \vdash \sigma : \Sigma \qquad \mathfrak{q} \sqsubseteq \mathsf{A}}{\Psi \vdash \sigma, \mathfrak{l} \mapsto (\mathfrak{q}, v, \mathfrak{f}) : \Sigma}$$

3.22 $\vdash \tau \downarrow \mathfrak{q}$

$$\frac{\bullet \vdash \tau \preceq \mathsf{A}}{\vdash \tau \downarrow \mathsf{U}} \qquad \frac{}{\vdash \tau \downarrow \mathsf{R}} \qquad \frac{\bullet \vdash \tau \preceq \mathsf{A}}{\vdash \tau \downarrow \mathsf{A}} \qquad \frac{}{\vdash \tau \downarrow \mathsf{L}}$$

3.23 $\Sigma \vdash \theta : \Theta$

$$\frac{}{\bullet \vdash \bullet : \bullet} \qquad \frac{\Sigma_\star \vdash \theta : \Theta \qquad \vdash \tau \downarrow \mathfrak{q} \qquad \bullet; \Sigma_l \vdash \mathfrak{l} : \tau \qquad \bullet \vdash \Sigma_l \odot \Sigma_\star \rightsquigarrow \Sigma}{\Sigma \vdash \theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l}) : \Theta, \mathfrak{p} \mapsto (\mathfrak{q}, \tau)}$$

$$\frac{\Sigma \vdash \theta : \Theta \qquad \mathfrak{q} \sqsubseteq \mathsf{A}}{\Sigma \vdash \theta, \mathfrak{p} \mapsto (\mathfrak{q}, \mathfrak{l}) : \Theta}$$

3.24 $\vdash \upsilon : \Upsilon$

$$\frac{}{\vdash {}^{\mathfrak{q}}\mathtt{live} : {}^{\mathfrak{q}}\mathsf{pre}} \qquad \frac{\mathfrak{q} \sqsubseteq \mathsf{A}}{\vdash {}^{\mathfrak{q}}\mathtt{live} : \mathsf{abs}} \qquad \frac{}{\vdash \mathtt{dead} : \mathsf{abs}}$$

3.25 $\Sigma \vdash \psi : \Psi$

$$\frac{}{\bullet \vdash \bullet : \bullet} \qquad \frac{\vdash \upsilon : \Upsilon \qquad \Sigma_\star \vdash \psi : \Psi \qquad \Sigma_r \vdash \theta : \Theta \qquad \bullet \vdash \Sigma_r \odot \Sigma_\star \rightsquigarrow \Sigma}{\Sigma \vdash \psi, \mathfrak{r} \mapsto (\upsilon, \theta) : \Psi, \mathfrak{r} \mapsto (\Upsilon, \Theta)}$$

3.26 $\vdash (\sigma, \psi) : \Sigma$

$$\frac{\Sigma_1 \vdash \psi : \Psi \qquad \bullet \vdash \Sigma_1 \odot \Sigma_2 \rightsquigarrow \Sigma \qquad \Psi \vdash \sigma : \Sigma}{\vdash (\sigma, \psi) : \Sigma_2}$$

4 Safety

Theorem 1 (Preservation)

If $(\sigma_1, \psi_1, e_1) \longmapsto^* (\sigma_2, \psi_2, e_2)$ *and* $\vdash (\sigma_1, \psi_1) : \Sigma_1$ *and* $\bullet; \bullet; \Sigma_1 \vdash e_1 : \tau$,
then there exists Σ_2 *such that* $\vdash (\sigma_2, \psi_2) : \Sigma_2$ *and* $\bullet; \bullet; \Sigma_2 \vdash e_2 : \tau$.

Theorem 2 (Progress)

If $\vdash (\sigma_1, \psi_1) : \Sigma_1$ *and* $\bullet; \bullet; \Sigma_1 \vdash e_1 : \tau$,
then either there exists l *such that* $e_1 \equiv l$
or there exists σ_2 *and* ψ_2 *and* e_2 *such that* $(\sigma_1, \psi_1, e_1) \longmapsto (\sigma_2, \psi_2, e_2)$.

Theorem 3 (Safety)

If $\vdash (\sigma_1, \psi_1) : \Sigma_1$ *and* $\bullet; \bullet; \Sigma_1 \vdash e_1 : \tau$ *and* $(\sigma_1, \psi_1, e_1) \longmapsto^* (\sigma_2, \psi_2, e_2)$,
then either there exists l *such that* $e_2 \equiv l$
or there exists σ_3 *and* ψ_3 *and* e_3 *such that* $(\sigma_2, \psi_2, e_2) \longmapsto (\sigma_3, \psi_3, e_3)$.