Hazel Phi: 11-type-constructors

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Syntax

Kind	κ	$::=$	$\mathtt{Type} \mid \mathtt{KHole} \mid \mathsf{S}_{\kappa}(\tau) \mid \Pi_{t::\kappa_1}.\kappa_2$
User Types	$\hat{\tau}$	$::=$	$t \mid \mathtt{bse} \mid \hat{\tau_1} \oplus \hat{\tau_2} \mid (\!\|\,\|\!)^{\mathtt{u}} \mid (\!\|\hat{\tau}\|\!)^{\mathtt{u}} \mid \lambda t{::}\mathtt{Type}.\hat{\tau} \mid \hat{\tau_1}\ \hat{\tau_2}$
Internal Types	τ	$::=$	$t \mid \mathtt{bse} \mid \tau_1 \oplus \tau_2 \mid (\!\|\,\|\!)^{\mathtt{u}} \mid (\!\|\tau\|\!)^{\mathtt{u}} \mid (\!\|t\|\!)^{\mathtt{u}} \mid \lambda t{::}\kappa.\tau \mid \tau_1\ \tau_2$
Base Types	$\mathtt{bse}$	$::=$	$\mathtt{Int} \mid \mathtt{Float} \mid \mathtt{Bool}$
BinOp	$\oplus$	$::=$	$\times \mid + \mid \rightarrow$
Type Pattern			
User Expression			
Internal Expression			

Declaratives

$\boxed{\Delta; \Phi \vdash \tau ::> \kappa}$ τ has principal (well formed) kind κ

$$\frac{\Delta; \Phi \vdash \mathsf{OK}}{\Delta; \Phi \vdash \mathtt{bse} ::> \mathsf{S}_{\mathtt{Type}}(\mathtt{bse})}\ (1) \qquad \frac{\Delta; \Phi_1, t{::}\kappa, \Phi_2 \vdash \mathsf{OK}}{\Delta; \Phi \vdash t ::> \mathsf{S}_{\kappa}(t)}\ (2) \qquad \frac{\Delta; \Phi \vdash \tau_1{::}\mathtt{Type} \qquad \Delta; \Phi \vdash \tau_2{::}\mathtt{Type}}{\Delta; \Phi \vdash \tau_1 \oplus \tau_2 ::> \mathsf{S}_{\mathtt{Type}}(\tau_1 \oplus \tau_2)}\ (3)$$

$$\frac{\Delta_1, \mathtt{u}{::}\kappa, \Delta_2; \Phi \vdash \mathsf{OK}}{\Delta; \Phi \vdash (\!|\,|\!)^{\mathtt{u}} ::> \mathsf{S}_{\kappa}((\!|\,|\!)^{\mathtt{u}})}\ (4) \qquad \frac{\Delta_1, \mathtt{u}{::}\kappa, \Delta_2; \Phi \vdash \mathsf{OK} \qquad \Delta; \Phi \vdash \tau{::}\kappa_1}{\Delta; \Phi \vdash (\!|\tau|\!)^{\mathtt{u}} ::> \mathsf{S}_{\kappa}((\!|\tau|\!)^{\mathtt{u}})}\ (5)$$

$$\frac{\Delta_1, \mathtt{u}{::}\kappa, \Delta_2; \Phi \vdash \mathsf{OK} \qquad t \notin \mathsf{dom}(\Phi)}{\Delta; \Phi \vdash (\!|t|\!)^{\mathtt{u}} ::> \mathsf{S}_{\kappa}((\!|t|\!)^{\mathtt{u}})}\ (6) \qquad \frac{\Delta; \Phi, t{::}\kappa_1 \vdash \tau ::> \kappa_2}{\Delta; \Phi \vdash \lambda t{::}\kappa_1.\tau ::> \mathsf{S}_{\Pi_{t::\kappa_1}.\kappa_2}(\lambda t{::}\kappa_1.\tau)}\ (7)$$

$$\frac{\Delta; \Phi \vdash \tau_1 ::> \kappa \qquad \Delta; \Phi \vdash \kappa \overset{\blacktriangleright}{\scriptstyle\Pi} \Pi_{t::\kappa_1}.\kappa_2 \qquad \Delta; \Phi \vdash \tau_2{::}\kappa_1}{\Delta; \Phi \vdash \tau_1\ \tau_2 ::> [\tau_2/t]\kappa_2}\ (8)$$

$\boxed{\Delta; \Phi \vdash \tau{::}\kappa}$ τ is well formed at kind κ

$$\frac{\Delta; \Phi \vdash \tau ::> \kappa}{\Delta; \Phi \vdash \tau{::}\kappa}\ (9) \qquad \frac{\Delta; \Phi \vdash \tau ::> \mathsf{S}_{\kappa}(\tau)}{\Delta; \Phi \vdash \tau{::}\kappa}\ (10) \qquad \frac{\Delta; \Phi \vdash \tau{::}\mathsf{S}_{\kappa}(\tau_1) \qquad \Delta; \Phi \vdash \tau_1{::}\kappa}{\Delta; \Phi \vdash \tau{::}\kappa}\ (11)$$

$$\frac{\Delta; \Phi \vdash \tau ::> \kappa_1 \qquad \Delta; \Phi \vdash \kappa_1 \lesssim \kappa}{\Delta; \Phi \vdash \tau{::}\kappa}\ (12)$$

$$\frac{\Delta; \Phi \vdash \tau{::}\kappa}{\Delta; \Phi \vdash \tau{::}\mathsf{S}_{\kappa}(\tau)}\ (13)$$

$\boxed{\Delta; \Phi \vdash \kappa \overset{\blacktriangleright}{\Pi} \mathtt{\Pi}_{t::\kappa_1}.\kappa_2}$ κ has matched Π-kind $\mathtt{\Pi}_{t::\kappa_1}.\kappa_2$

$$\frac{}{\Delta; \Phi \vdash \mathtt{KHole} \overset{\blacktriangleright}{\Pi} \mathtt{\Pi}_{t::\mathtt{KHole}}.\mathtt{KHole}} \ (14) \qquad \frac{\Delta; \Phi \vdash \kappa \equiv \mathtt{S}_{\mathtt{KHole}}(\tau_1)}{\Delta; \Phi \vdash \kappa \overset{\blacktriangleright}{\Pi} \mathtt{\Pi}_{t::\kappa}.\kappa} \ (15) \qquad \frac{\Delta; \Phi \vdash \kappa \equiv \mathtt{\Pi}_{t::\kappa_1}.\kappa_2}{\Delta; \Phi \vdash \kappa \overset{\blacktriangleright}{\Pi} \mathtt{\Pi}_{t::\kappa_1}.\kappa_2} \ (16)$$

$\boxed{\Delta; \Phi \vdash \kappa_1 \equiv \kappa_2}$ κ_1 is equivalent to κ_2

$$\frac{\Delta; \Phi \vdash \kappa \ \mathsf{OK}}{\Delta; \Phi \vdash \kappa \equiv \kappa} \ (17) \qquad \frac{\Delta; \Phi \vdash \kappa_2 \equiv \kappa_1}{\Delta; \Phi \vdash \kappa_1 \equiv \kappa_2} \ (18) \qquad \frac{\Delta; \Phi \vdash \kappa_1 \equiv \kappa_3 \qquad \Delta; \Phi \vdash \kappa_3 \equiv \kappa_2}{\Delta; \Phi \vdash \kappa_1 \equiv \kappa_2} \ (19)$$

$$\frac{\Delta; \Phi \vdash \tau :: \mathtt{S}_{\kappa}(\tau_1)}{\Delta; \Phi \vdash \mathtt{S}_{\mathtt{S}_{\kappa}(\tau_1)}(\tau) \equiv \mathtt{S}_{\kappa}(\tau_1)} \ (20) \qquad \frac{\Delta; \Phi \vdash \tau :: \mathtt{\Pi}_{t::\kappa_1}.\kappa_2}{\Delta; \Phi \vdash \mathtt{S}_{\mathtt{\Pi}_{t::\kappa_1}.\kappa_2}(\tau) \equiv \mathtt{\Pi}_{t::\kappa_1}.\mathtt{S}_{\kappa_2}(\tau\ t)} \ (21)$$

$$\frac{\Delta; \Phi \vdash \kappa_1 \equiv \kappa_2 \qquad \Delta; \Phi, t::\kappa_1 \vdash \kappa_3 \equiv \kappa_4}{\Delta; \Phi \vdash \mathtt{\Pi}_{t::\kappa_1}.\kappa_2 \equiv \mathtt{\Pi}_{t::\kappa_3}.\kappa_4} \ (22) \qquad \frac{\Delta; \Phi \vdash \tau_1 \overset{\kappa}{\equiv} \tau_2}{\Delta; \Phi \vdash \mathtt{S}_{\kappa}(\tau_1) \equiv \mathtt{S}_{\kappa}(\tau_2)} \ (23)$$

$\boxed{\Delta; \Phi \vdash \kappa_1 \lesssim \kappa_2}$ κ_1 is a consistent subkind of κ_2

$$\frac{\Delta; \Phi \vdash \kappa \ \mathsf{OK}}{\Delta; \Phi \vdash \mathtt{KHole} \lesssim \kappa} \ (24) \qquad \frac{\Delta; \Phi \vdash \kappa \ \mathsf{OK}}{\Delta; \Phi \vdash \kappa \lesssim \mathtt{KHole}} \ (25) \qquad \frac{\Delta; \Phi \vdash \mathtt{S}_{\mathtt{KHole}}(\tau) \ \mathsf{OK} \qquad \Delta; \Phi \vdash \kappa \ \mathsf{OK}}{\Delta; \Phi \vdash \mathtt{S}_{\mathtt{KHole}}(\tau) \lesssim \kappa} \ (26)$$

$$\frac{\Delta; \Phi \vdash \kappa \ \mathsf{OK} \qquad \Delta; \Phi \vdash \mathtt{S}_{\mathtt{KHole}}(\tau) \ \mathsf{OK}}{\Delta; \Phi \vdash \kappa \lesssim \mathtt{S}_{\mathtt{KHole}}(\tau)} \ (27)$$

$$\frac{\Delta; \Phi \vdash \kappa_1 \equiv \kappa_2}{\Delta; \Phi \vdash \kappa_1 \lesssim \kappa_2} \ (28) \qquad \frac{\Delta; \Phi \vdash \kappa_1 \equiv \kappa_3 \qquad \Delta; \Phi \vdash \kappa_3 \lesssim \kappa_4 \qquad \Delta; \Phi \vdash \kappa_4 \equiv \kappa_2}{\Delta; \Phi \vdash \kappa_1 \lesssim \kappa_2} \ (29)$$

$$\frac{\Delta; \Phi \vdash \mathtt{S}_{\kappa}(\tau) \ \mathsf{OK}}{\Delta; \Phi \vdash \mathtt{S}_{\kappa}(\tau) \lesssim \kappa} \ (30) \qquad \frac{\Delta; \Phi \vdash \kappa_3 \lesssim \kappa_1 \qquad \Delta; \Phi, t::\kappa_3 \vdash \kappa_2 \lesssim \kappa_4}{\Delta; \Phi \vdash \mathtt{\Pi}_{t::\kappa_1}.\kappa_2 \lesssim \mathtt{\Pi}_{t::\kappa_3}.\kappa_4} \ (31)$$

$$\frac{\Delta; \Phi \vdash \kappa_1 \lesssim \kappa_2 \qquad \Delta; \Phi \vdash \tau_1 \overset{\kappa_1}{\equiv} \tau_2}{\Delta; \Phi \vdash \mathtt{S}_{\kappa_1}(\tau_1) \lesssim \mathtt{S}_{\kappa_2}(\tau_2)} \ (32)$$

$\boxed{\Delta;\Phi\vdash\tau_1\overset{\kappa}{\equiv}\tau_2}$ τ_1 is provably equivalent to τ_2 at kind κ

$$\frac{\Delta;\Phi\vdash\tau_1 ::> \kappa_1 \qquad \Delta;\Phi\vdash\kappa_1\equiv \mathtt{S}_\kappa(\tau_2)}{\Delta;\Phi\vdash\tau_1\overset{\kappa}{\equiv}\tau_2}\ (33)$$

$$\frac{\Delta;\Phi\vdash\tau_1::\Pi_{t::\kappa_1}.\kappa_3 \qquad \Delta;\Phi\vdash\tau_2::\Pi_{t::\kappa_1}.\kappa_4 \qquad \Delta;\Phi,t::\kappa_1\vdash\tau_1\ t\overset{\kappa_2}{\equiv}\tau_2\ t}{\Delta;\Phi\vdash\tau_1\overset{\Pi_{t::\kappa_1}.\kappa_2}{\equiv}\tau_2}\ (34) \qquad \frac{\Delta;\Phi\vdash\tau_1\overset{\mathtt{S}_\kappa(\tau)}{\equiv}\tau_2}{\Delta;\Phi\vdash\tau_1\overset{\kappa}{\equiv}\tau_2}\ (35)$$

$$\frac{\Delta;\Phi\vdash\tau_1\overset{\Pi_{t::\kappa_1}.\kappa_2}{\equiv}\tau_3 \qquad \Delta;\Phi\vdash\tau_2\overset{\kappa_1}{\equiv}\tau_4}{\Delta;\Phi\vdash\tau_1\ \tau_2\overset{[\tau_2/t]\kappa_2}{\equiv}\tau_3\ \tau_4}\ (36)$$

$$\frac{\Delta;\Phi\vdash\tau::\kappa}{\Delta;\Phi\vdash\tau\overset{\kappa}{\equiv}\tau}\ (37) \qquad \frac{\Delta;\Phi\vdash\tau_2\overset{\kappa}{\equiv}\tau_1}{\Delta;\Phi\vdash\tau_1\overset{\kappa}{\equiv}\tau_2}\ (38) \qquad \frac{\Delta;\Phi\vdash\tau_1\overset{\kappa}{\equiv}\tau_3 \qquad \Delta;\Phi\vdash\tau_3\overset{\kappa}{\equiv}\tau_1}{\Delta;\Phi\vdash\tau_1\overset{\kappa}{\equiv}\tau_2}\ (39)$$

$$\frac{\Delta;\Phi\vdash\tau_1\overset{\mathtt{Type}}{\equiv}\tau_3 \qquad \Delta;\Phi\vdash\tau_2\overset{\mathtt{Type}}{\equiv}\tau_4}{\Delta;\Phi\vdash\tau_1\oplus\tau_2\overset{\mathtt{Type}}{\equiv}\tau_3\oplus\tau_4}\ (40) \qquad \frac{\Delta;\Phi\vdash\kappa_1\equiv\kappa_2 \qquad \Delta;\Phi,t::\kappa_1\vdash\tau_1\overset{\kappa}{\equiv}\tau_2}{\Delta;\Phi\vdash\lambda t::\kappa_1.\tau_1\overset{\Pi_{t::\kappa_1}.\kappa}{\equiv}\lambda t::\kappa_2.\tau_2}\ (41)$$

$$\frac{\Delta;\Phi\vdash\tau_1\overset{\kappa_1}{\equiv}\tau_2 \qquad \Delta;\Phi\vdash\kappa_1\equiv\kappa}{\Delta;\Phi\vdash\tau_1\overset{\kappa}{\equiv}\tau_2}\ (42)$$

$\boxed{\Delta;\Phi\vdash\kappa\ \mathsf{OK}}$ κ is well formed

$$\frac{\Delta;\Phi\vdash\mathsf{OK}}{\Delta;\Phi\vdash\mathtt{Type}\ \mathsf{OK}}\ (43) \qquad \frac{\Delta;\Phi\vdash\mathsf{OK}}{\Delta;\Phi\vdash\mathtt{KHole}\ \mathsf{OK}}\ (44) \qquad \frac{\Delta;\Phi\vdash\tau::\kappa}{\Delta;\Phi\vdash\mathtt{S}_\kappa(\tau)\ \mathsf{OK}}\ (45)$$

$$\frac{\Delta;\Phi\vdash\kappa_1\ \mathsf{OK} \qquad \Delta;\Phi,t::\kappa_1\vdash\kappa_2\ \mathsf{OK}}{\Delta;\Phi\vdash\Pi_{t::\kappa_1}.\kappa_2\ \mathsf{OK}}\ (46)$$

$\boxed{\Delta;\Phi\vdash\mathsf{OK}}$ Context is well formed

$$\frac{}{;\vdash\mathsf{OK}}\ (47) \qquad \frac{\Delta;\Phi\vdash\kappa\ \mathsf{OK}}{\Delta;\Phi,t::\kappa\vdash\mathsf{OK}}\ (48) \qquad \frac{\Delta;\Phi\vdash\kappa\ \mathsf{OK}}{\Delta,\mathrm{u}::\kappa;\Phi\vdash\mathsf{OK}}\ (49)$$

Variables implicitly assumed to be fresh as necessary

Metatheory

Lemma 1 (Weakening)**.** *If $\Delta;\Phi\vdash\tau::\kappa$, then $\Delta;\Phi,t::\kappa_1\vdash\tau::\kappa$ when $\Delta;\Phi,t::\kappa_1\vdash\mathsf{OK}$*

Proof. By rule induction/length of proof.
L1. (9)

□

Proof. By rule induction/length of proof.
L2. (9)

□

Lemma 2 (OK-PK)**.** *If $\Delta;\Phi\vdash\tau ::> \kappa$, then $\Delta;\Phi\vdash\mathsf{OK}$ and $\Delta;\Phi\vdash\kappa\ \mathsf{OK}$*

Lemma 3 (OK-WFaK)**.** *If* $\Delta;\Phi \vdash \tau{::}\kappa$, *then* $\Delta;\Phi \vdash \mathit{OK}$ *and* $\Delta;\Phi \vdash \kappa\ \mathit{OK}$

Lemma 4 (OK-MatchPi)**.** *If* $\Delta;\Phi \vdash \kappa \overset{\blacktriangleright}{\scriptstyle\Pi} \Pi_{t::\kappa_1}.\kappa_2$, *then* $\Delta;\Phi \vdash \mathit{OK}$ *and* $\Delta;\Phi \vdash \kappa\ \mathit{OK}$ *and* $\Delta;\Phi \vdash \Pi_{t::\kappa_1}.\kappa_2\ \mathit{OK}$

Lemma 5 (OK-KEquiv)**.** *If* $\Delta;\Phi \vdash \kappa_1 \equiv \kappa_2$, *then* $\Delta;\Phi \vdash \mathit{OK}$ *and* $\Delta;\Phi \vdash \kappa_1\ \mathit{OK}$ *and* $\Delta;\Phi \vdash \kappa_2\ \mathit{OK}$

Lemma 6 (OK-CSK)**.** *If* $\Delta;\Phi \vdash \kappa_1 \lesssim \kappa_2$, *then* $\Delta;\Phi \vdash \mathit{OK}$ *and* $\Delta;\Phi \vdash \kappa_1\ \mathit{OK}$ *and* $\Delta;\Phi \vdash \kappa_2\ \mathit{OK}$

Lemma 7 (OK-KWF)**.** *If* $\Delta;\Phi \vdash \kappa\ \mathit{OK}$, *then* $\Delta;\Phi \vdash \mathit{OK}$

Lemma 8 (OK-Substitution)**.**
If $\Delta;\Phi \vdash \tau_L{::}\kappa_{L1}$ *and* $\Delta;\Phi, t_L{::}\kappa_{L1} \vdash \kappa_{L2}\ \mathit{OK}$, *then* $\Delta;\Phi \vdash \mathit{OK}$ *and* $\Delta;\Phi \vdash [\tau_L/t_L]\kappa_{L2}\ \mathit{OK}$
(induction on $\Delta;\Phi, t_L{::}\kappa_{L1} \vdash \kappa_{L2}\ \mathit{OK}$*)*

Lemma 9 (K-Substitution)**.**
If $\Delta;\Phi \vdash \tau_{L1}{::}\kappa_{L1}$ *and* $\Delta;\Phi, t_L{::}\kappa_{L1} \vdash \tau_{L2}{::}\kappa_{L2}$, *then* $\Delta;\Phi \vdash [\tau_{L1}/t_L]\tau_{L2}{::}[\tau_{L1}/t_L]\kappa_{L2}$
(induction on $\Delta;\Phi, t_L{::}\kappa_{L1} \vdash \tau_{L2}{::}\kappa_{L2}$*)*

Proof. By simultaneous rule induction/length of proof.
The interesting cases per lemma:

OK-PK.	(1)	$\Delta;\Phi \vdash \mathtt{bse}{::}\mathtt{S}_{\mathtt{Type}}(\mathtt{bse})$	by (9)
		$\Delta;\Phi \vdash \mathtt{bse}{::}\mathtt{Type}$	by (10)
	*	$\Delta;\Phi \vdash \mathtt{S}_{\mathtt{Type}}(\mathtt{bse})\ \mathsf{OK}$	by (43)
	*	$\Delta;\Phi \vdash \mathsf{OK}$	by premiss
	(8)		bad
OK-WFaK.	(12)	$\Delta;\Phi \vdash \tau_2{::}\kappa$	by (10)
	*	$\Delta;\Phi \vdash \mathtt{S}_\kappa(\tau_2)\ \mathsf{OK}$	by (43)
OK-KEquiv.	(22)	$\Delta;\Phi \vdash \tau\ t \mathrel{::>} \kappa$	
OK-Substitution.	(41)	$\Delta;\Phi, t_L{::}\kappa_{L1} \vdash \mathsf{OK}$	premiss (41)
		$\Delta;\Phi \vdash \kappa_{L1}\ \mathsf{OK}$	by subderivation premiss (46)
	*	$\Delta;\Phi \vdash \mathsf{OK}$	by OK-KWF
	*	$\Delta;\Phi \vdash [\tau_L/t_L]\mathtt{Type}\ \mathsf{OK}$	by (41) and degenerate subst
	(43)	$\Delta;\Phi, t_L{::}\kappa_{L1} \vdash \tau{::}\kappa$	premiss (43)
		$\Delta;\Phi, t_L{::}\kappa_{L1} \vdash \mathsf{OK}$	by OK-WFaK
		$\Delta;\Phi \vdash \kappa_{L1}\ \mathsf{OK}$	by subderivation premiss (46)
	*	$\Delta;\Phi \vdash \mathsf{OK}$	by OK-KWF
		$\Delta;\Phi \vdash [\tau_{L1}/t_L]\tau{::}[\tau_{L1}/t_L]\kappa$	by K-Substitution on premiss
	*	$\Delta;\Phi \vdash [\tau_L/t_L]\mathtt{S}_\kappa(\tau)\ \mathsf{OK}$	by (43)

□

Lemma 10 (PK-Unicity)**.** *If* $\Delta;\Phi \vdash \tau_L \mathrel{::>} \kappa_{L1}$ *and* $\Delta;\Phi \vdash \tau_L \mathrel{::>} \kappa_{L2}$ *then* κ_{L1} *is* κ_{L2}

Lemma 11. *If* $\Delta;\Phi \vdash \tau \mathrel{::>} \kappa_1$ *and* $\Delta;\Phi \vdash \tau{::}\kappa_2$, *then* $\Delta;\Phi \vdash \kappa_1 \lesssim \kappa_2$