# Gradual Intersection Types

Pedro Ângelo

January 5, 2018

## 1 Language Definition

Syntax

$$
\begin{aligned}
&\mathit{Types}\;\; T ::= \mathit{Int} \mid \mathit{Bool} \mid \mathit{Dyn} \mid T \rightarrow T' \mid T \cap \ldots \cap T\\
&\qquad\quad T' ::= \mathit{Int} \mid \mathit{Bool} \mid \mathit{Dyn} \mid T' \rightarrow T'\\
&\mathit{Expressions}\;\; e \;::= x \mid \lambda x : T\;.\;e \mid e\;e \mid n \mid \mathit{true} \mid \mathit{false} \mid e + e\\
&\qquad\qquad\qquad\quad \mid e : T' \Rightarrow^{l} T' \mid e : c \cap \ldots \cap c \mid \mathit{blame}_T\; l\\
&\mathit{Ground\ Types}\; G \;::= \mathit{Int} \mid \mathit{Bool} \mid \mathit{Dyn} \rightarrow \mathit{Dyn}\\
&\mathit{Casts}\;\; c \;::= c : T' \Rightarrow^{l} T'\;{}^{n} \mid \mathit{blame}\; T'\; T'\; l\;{}^{n} \mid \varnothing\; T'\;{}^{n}\\
&\mathit{Values}\;\; v \;::= x \mid \lambda x : T\;.\;e \mid n \mid \mathit{true} \mid \mathit{false} \mid \mathit{blame}_T\; l\\
&\qquad\qquad \mid v : G \Rightarrow^{l} \mathit{Dyn}\\
&\qquad\qquad \mid v : T'_1 \rightarrow T'_2 \Rightarrow^{l} T'_3 \rightarrow T'_4\\
&\qquad\qquad \mid v : cv_1 \cap \ldots \cap cv_n \;\mathit{such\ that}\\
&\qquad\qquad \neg(\forall_{i \in 1..n}\;.\;cv_i = \mathit{blame}\; T'\; T'\; l\;{}^{m}) \wedge\\
&\qquad\qquad \neg(\forall_{i \in 1..n}\;.\;cv_i = \varnothing\; T'\;{}^{m})\\
&\mathit{Cast\ Values}\;\; cv \;::= cv1 \mid cv2\\
&\qquad\qquad cv1 \;::= \varnothing\; T'\;{}^{n} : G \Rightarrow^{l} \mathit{Dyn}\;{}^{n}\\
&\qquad\qquad\qquad \mid \varnothing\; T'\;{}^{n} : T'_1 \rightarrow T'_2 \Rightarrow^{l} T'_3 \rightarrow T'_4\\
&\qquad\qquad\qquad \mid cv1 : G \Rightarrow^{l} \mathit{Dyn}\;{}^{n}\\
&\qquad\qquad\qquad \mid cv1 : T'_1 \rightarrow T'_2 \Rightarrow^{l} T'_3 \rightarrow T'_4\\
&\qquad\qquad cv2 \;::= \mathit{blame}\; T'\; T'\; l\;{}^{n}\\
&\qquad\qquad\qquad \mid \varnothing\; T'\;{}^{n}
\end{aligned}
$$

---

Figure 1: Gradual Intersection System

$\boxed{\Gamma \vdash_{\cap G} e : T}$ Typing

$$\frac{\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap G} \; e : T}{\Gamma \vdash_{\cap G} \lambda x : T_1 \cap \ldots \cap T_n \; . \; e : T_1 \cap \ldots \cap T_n \to T} \to I$$

$$\frac{\Gamma, x : T_i \vdash_{\cap G} \; e : T}{\Gamma \vdash_{\cap G} \lambda x : T_1 \cap \ldots \cap T_n \; . \; e : T_i \to T} \to I'$$

$$\frac{\begin{array}{cc} \Gamma \vdash_{\cap G} e_1 : PM & PM \rhd T_1 \cap \ldots \cap T_n \to T \\ \Gamma \vdash_{\cap G} e_2 : T_1' \cap \ldots \cap T_n' & T_1' \cap \ldots \cap T_n' \sim T_1 \cap \ldots \cap T_n \end{array}}{\Gamma \vdash_{\cap G} e_1 \; e_2 : T} \to E$$

$$\frac{\Gamma \vdash_{\cap G} e : T_1 \; \ldots \; \Gamma \vdash_{\cap G} e : T_n}{\Gamma \vdash_{\cap G} e : T_1 \cap \ldots \cap T_n} \cap I \qquad \frac{x : T_1 \cap \ldots \cap T_n \in \Gamma}{\Gamma \vdash_{\cap G} x : T_i} \cap E$$

$\boxed{T \sim T}$ Consistency

$$\frac{}{B \sim B} \qquad \frac{}{T \sim Dyn} \qquad \frac{}{Dyn \sim T} \qquad \frac{T_1 \sim T_3 \qquad T_2 \sim T_4}{T_1 \to T_2 \sim T_3 \to T_4}$$

$$\frac{T_1 \sim T_1' \; \ldots \; T_n \sim T_n'}{T_1 \cap \ldots \cap T_n \sim T_1' \cap \ldots \cap T_n'} \qquad \frac{T \sim T_1 \; \ldots \; T \sim T_n}{T \sim T_1 \cap \ldots \cap T_n} \qquad \frac{T_1 \sim T \; \ldots \; T_n \sim T}{T_1 \cap \ldots \cap T_n \sim T}$$

$\boxed{T \rhd T}$ Pattern Matching

$$\frac{}{(T_1 \to T_2) \rhd T_1 \to T_2} \qquad \frac{}{Dyn \rhd Dyn \to Dyn}$$

$\boxed{T \sqsubseteq T}$ Type Precision

$$\frac{}{Dyn \sqsubseteq T} \qquad \frac{}{B \sqsubseteq B} \qquad \frac{T_1 \sqsubseteq T_3 \qquad T_2 \sqsubseteq T_4}{T_1 \to T_2 \sqsubseteq T_3 \to T_4}$$

$$\frac{T_1 \sqsubseteq T_1' \; \ldots \; T_n \sqsubseteq T_n'}{T_1 \cap \ldots \cap T_n \sqsubseteq T_1' \cap \ldots \cap T_n'} \qquad \frac{T \sqsubseteq T_1 \; \ldots \; T \sqsubseteq T_n}{T \sqsubseteq T_1 \cap \ldots \cap T_n} \qquad \frac{T_1 \sqsubseteq T \; \ldots \; T_n \sqsubseteq T}{T_1 \cap \ldots \cap T_n \sqsubseteq T}$$

$\boxed{e \sqsubseteq e}$ Term Precision

$$\frac{}{x \sqsubseteq e} \qquad \frac{T \sqsubseteq T' \qquad e \sqsubseteq e'}{\lambda x : T \; . \; e \sqsubseteq \lambda x : T' \; . \; e'} \qquad \frac{e_1 \sqsubseteq e_1' \qquad e_2 \sqsubseteq e_2'}{e_1 \; e_2 \sqsubseteq e_1' \; e_2'}$$

Figure 2: Gradual Intersection Type System ($\vdash_{\cap G}$)

$\boxed{\Gamma \vdash_{\cap CC} e : T}$ Typing

$$\textit{rules in Figure 2 and}$$

$$\frac{\Gamma \vdash_{\cap CC} e : T_1 \qquad T_1 \sim T_2}{\Gamma \vdash_{\cap CC} (e : T_1 \Rightarrow^l T_2) : T_2} \text{ T-CAST} \qquad \frac{}{\Gamma \vdash_{\cap CC} blame_T\ l : T} \text{ T-BLAME}$$

$$\frac{\begin{array}{c}\Gamma \vdash_{\cap CC} e : T \qquad \vdash_{\cap IC} c_1 : T_1\ \ldots\ \vdash_{\cap IC} c_n : T_n \\ initialType(c_1) \cap \ldots \cap initialType(c_n) =_{\cap} T\end{array}}{\Gamma \vdash_{\cap CC} (e : c_1 \cap \ldots \cap c_n) : T_1 \cap \ldots \cap T_n} \text{ T-INTERSECTIONCAST}$$

$\boxed{\text{initialType(c)} = \text{T}}$

$$initialType(c : T_1 \Rightarrow^l T_2\ ^n) = initialType(c)$$

$$initialType(\varnothing\ T\ ^n) = T$$

$$initialType(blame\ T_I\ T_F\ l\ ^n) = T_I$$

$\boxed{\text{finalType(c)} = \text{T}}$

$$finalType(c : T_1 \Rightarrow^l T_2\ ^n) = T_2$$

$$finalType(\varnothing\ T\ ^n) = T$$

$$finalType(blame\ T_I\ T_F\ l\ ^n) = T_F$$

Figure 3: Intersection Cast Calculus ($\vdash_{\cap CC}$)

$\boxed{\Gamma \vdash_{\cap CC} e \rightsquigarrow e : T}$ Compilation

$$\frac{x : T_1 \cap \ldots \cap T_n \in \Gamma}{\Gamma \vdash_{\cap CC} x \rightsquigarrow x : T_i}$$

$$\frac{\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap CC} e \rightsquigarrow e' : T}{\Gamma \vdash_{\cap CC} (\lambda x : T_1 \cap \ldots \cap T_n \ . \ e) \rightsquigarrow (\lambda x : T_1 \cap \ldots \cap T_n \ . \ e') : T_1 \cap \ldots \cap T_n \to T}$$

$$\frac{\begin{array}{c}\Gamma \vdash_{CC} e_1 \rightsquigarrow e_1' : PM \qquad PM \rhd T_1 \cap \ldots \cap T_n \to T \\ \Gamma \vdash_{CC} e_2 \rightsquigarrow e_2' : T_1' \cap \ldots \cap T_n' \qquad T_1' \cap \ldots \cap T_n' \sim T_1 \cap \ldots \cap T_n \\ e_1'' = addCasts(getInstances(PM),\ getInstances(T_1 \cap \ldots \cap T_n \to T),\ e_1') \\ e_2'' = addCasts(getInstances(T_1' \cap \ldots \cap T_n'),\ getInstances(T_1 \cap \ldots \cap T_n),\ e_2')\end{array}}{\Gamma \vdash_{CC} e_1\ e_2 \rightsquigarrow e_1''\ e_2'' : T}$$

$\boxed{\text{getInstances(T)} = \{\text{T}\}}$

$$getInstances(Int) = \{Int\}$$

$$getInstances(Bool) = \{Bool\}$$

$$getInstances(Dyn) = \{Dyn\}$$

$$\begin{array}{c} getInstances(T_1 \to T_2) = \\ let\ \{T_{11}, \ldots, T_{1n}\} = getInstances(T_1)\ in\ \{T_{11} \to T_2, \ldots, T_{1n} \to T_2\}\end{array}$$

$$\begin{array}{c} getInstances(T_1 \cap \ldots \cap T_n) = \\ let\ \{T_{11}, \ldots, T_{1m}\} = getInstances(T_1) \\ \ldots \\ let\ \{T_{n1}, \ldots, T_{nj}\} = getInstances(T_n) \\ in\ \{T_{11}, \ldots, T_{1m}, \ldots, T_{n1}, \ldots, T_{nj}\}\end{array}$$

$\boxed{\text{addCasts(\{T\}, \{T\}, e)} = \text{e}}$

$$addCasts(\{T_1\}, \{T_2\}, e) = e : T_1 \Rightarrow^l T_2$$

$$\begin{array}{c} addCasts(\{T_{11}, \ldots, T_{1n}\}, \{T_{21}, \ldots, T_{2n}\}, e) = \\ e : (\varnothing\ T_{11}\ ^0 : T_{11} \Rightarrow^l T_{21}\ ^0) \cap \ldots \cap (\varnothing\ T_{1n}\ ^0 : T_{1n} \Rightarrow^l T_{2n}\ ^0)\end{array}$$

$$\begin{array}{c} addCasts(\{T_{11}, \ldots, T_{1n}\}, \{T_2\}, e) = \\ e : (\varnothing\ T_{11}\ ^0 : T_{11} \Rightarrow^l T_2\ ^0) \cap \ldots \cap (\varnothing\ T_{1n}\ ^0 : T_{1n} \Rightarrow^l T_2\ ^0)\end{array}$$

$$\begin{array}{c} addCasts(\{T_1\}, \{T_{21}, \ldots, T_{2n}\}, e) = \\ e : (\varnothing\ T_1\ ^0 : T_1 \Rightarrow^l T_{21}\ ^0) \cap \ldots \cap (\varnothing\ T_1\ ^0 : T_1 \Rightarrow^l T_{2n}\ ^0)\end{array}$$

Figure 4: Compilation to the Cast Calculus

$\boxed{e \longrightarrow_{\cap CC} e}$ Evaluation

*Simulate casts on data types*

$$\frac{\begin{array}{c} isValue\ v_1 : cv_1 \cap \ldots \cap cv_n \qquad \exists i \in 1..n\ .\ isArrowCompatible\ cv_i \\ (cv'_1, \ldots, cv'_m) = filter\ isArrowCompatible\ (cv_1, \ldots, cv_n) \\ ((c_{11}, c_{12}, r_1), \ldots, (c_{m1}, c_{m2}, r_m)) = map\ simulateArrow\ (cv'_1, \ldots, cv'_m) \end{array}}{\begin{array}{c} (v_1 : cv_1 \cap \ldots \cap cv_n)\ v_2 \longrightarrow_{\cap CC} \\ (v_1 : r_1 \cap \ldots \cap r_m)\ (v_2 : c_{11} \cap \ldots \cap c_{m1}) : c_{12} \cap \ldots \cap c_{m2} \end{array}} \textsc{Simulate}\cap$$

*Merge casts*

$$\frac{\begin{array}{c} isValue\ v : cv_1 \cap \ldots \cap cv_n \\ v : c'_1 \cap \ldots \cap c'_m = mergeIC(v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2) \end{array}}{v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2 \longrightarrow_{\cap CC} v : c'_1 \cap \ldots \cap c'_m} \textsc{MergeIC}\cap$$

$$\frac{\begin{array}{c} isValue\ v : T_1 \Rightarrow^l T_2 \\ v : c'_1 \cap \ldots \cap c'_m = mergeCI(v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n) \end{array}}{v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n \longrightarrow_{\cap CC} v : c'_1 \cap \ldots \cap c'_m} \textsc{MergeCI}\cap$$

$$\frac{\begin{array}{c} isValue\ v : cv_1 \cap \ldots \cap cv_n \\ v : c'_1 \cap \ldots \cap c'_j = mergeII(v : cv_1 \cap \ldots \cap cv_n : c_1 \cap \ldots \cap c_m) \end{array}}{v : cv_1 \cap \ldots \cap cv_n : c_1 \cap \ldots \cap c_m \longrightarrow_{\cap CC} v : c'_1 \cap \ldots \cap c'_j} \textsc{MergeII}\cap$$

*Evaluate intersection casts*

$$\frac{\begin{array}{c} \neg(\forall i \in 1..n\ .\ isCastValue\ c_i) \\ c_1 \longrightarrow_{\cap IC} cv_1 \ \ldots\ c_n \longrightarrow_{\cap IC} cv_n \end{array}}{v : c_1 \cap \ldots \cap c_n \longrightarrow_{\cap CC} v : cv_1 \cap \ldots \cap cv_n} \textsc{Evaluate}\cap$$

*Transition from cast values to values*

$$\frac{}{\begin{array}{c} v : blame\ T'_1\ T_1\ l_1\ ^{m_1} \cap \ldots \cap blame\ T'_n\ T_n\ l_n\ ^{m_n} \\ \longrightarrow_{\cap CC} blame_{(T_1 \cap \ldots \cap T_n)}\ l_1 \end{array}} \textsc{PropagateBlame}\cap$$

$$\frac{}{v : \varnothing\ T_1\ ^{m_1} \cap \ldots \cap \varnothing\ T_n\ ^{m_n} \longrightarrow_{\cap CC} v} \textsc{RemoveEmpty}\cap$$

Figure 5: Cast Calculus Semantics ($\longrightarrow_{\cap CC}$)

$\boxed{\vdash_{\cap IC} c : T}$ Typing

$$\frac{\vdash_{\cap IG} c : T_1 \qquad T_1 \sim T_2}{\vdash_{\cap IG} (c : T_1 \Rightarrow^{l} T_2\ ^{n}) : T_1}\ \text{T-SingleC} \qquad \frac{}{\vdash_{\cap IG} \varnothing\ T\ ^{n} : T}\ \text{T-EmptyC}$$

$$\frac{}{\vdash_{\cap IG} \mathit{blame}\ T_I\ T_F\ l\ ^{n} : T_F}\ \text{T-BlameC}$$

Figure 6: Intersection Casts Type System ($\vdash_{\cap IC}$)

$\boxed{c \longrightarrow_{\cap IC} c}$ Evaluation

*Push blame to top level*

$$\frac{}{blame\ T_I\ T_F\ l_1\ {}^{n_1} : T_1 \Rightarrow^{l_2} T_2\ {}^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ T_2\ l_1\ {}^{n_1}}\ \textsc{PushBlameC}$$

*Evaluate inside casts*

$$\frac{\neg(isCastValue\ c) \qquad c \longrightarrow_{\cap IC} c'}{c : T_1 \Rightarrow^{l} T_2\ {}^{n} \longrightarrow_{\cap IC} c' : T_1 \Rightarrow^{l} T_2\ {}^{n}}\ \textsc{EvaluateC}$$

*Detect success or failure of casts*

$$\frac{isCastValue1\ c \vee isEmptyCast\ c}{c : T \Rightarrow^{l} T\ {}^{n} \longrightarrow_{\cap IC} c}\ \textsc{IdentityC}$$

$$\frac{isCastValue1\ c \vee isEmptyCast\ c}{c : G \Rightarrow^{l_1} Dyn\ {}^{n_1} : Dyn \Rightarrow^{l_2} G\ {}^{n_2} \longrightarrow_{\cap IC} c}\ \textsc{SucceedC}$$

$$\frac{\begin{array}{c} isCastValue1\ c \vee isEmptyCast\ c \\ \neg(same\ ground\ G_1\ G_2) \qquad initialType(c) = T_I \end{array}}{c : G_1 \Rightarrow^{l_1} Dyn\ {}^{n_1} : Dyn \Rightarrow^{l_2} G_2\ {}^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ G_2\ l_2\ {}^{n_1}}\ \textsc{FailC}$$

*Mediate the transition between the two disciplines*

$$\frac{\begin{array}{c} isCastValue1\ c \vee isEmptyCast\ c \\ G\ is\ ground\ type\ of\ T \qquad \neg(ground\ T) \end{array}}{c : T \Rightarrow^{l} Dyn\ {}^{n} \longrightarrow_{\cap IC} c : T \Rightarrow^{l} G\ {}^{n} : G \Rightarrow^{l} Dyn\ {}^{n}}\ \textsc{GroundC}$$

$$\frac{\begin{array}{c} isCastValue1\ c \vee isEmptyCast\ c \\ G\ is\ ground\ type\ of\ T \qquad \neg(ground\ T) \end{array}}{c : Dyn \Rightarrow^{l} T\ {}^{n} \longrightarrow_{\cap IC} c : Dyn \Rightarrow^{l} G\ {}^{n} : G \Rightarrow^{l} T\ {}^{n}}\ \textsc{ExpandC}$$

Figure 7: Intersection Casts Semantics ($\longrightarrow_{\cap IC}$)

$\boxed{[e]_e = \mathrm{e}}$ Erase identity casts

$$[x]_e = x$$

$$[\lambda x : T\ .\ e]_e = \lambda x : T\ .\ [e]_e$$

$$[e_1\ e_2]_e = [e_1]_e\ [e_2]_e$$

$$[n]_e = n$$

$$[true]_e = true$$

$$[false]_e = false$$

$$[e_1 + e_2]_e = [e_1]_e + [e_2]_e$$

$$[e : T \Rightarrow^l T]_e = [e]_e$$

$$[e : T_1 \Rightarrow^l T_2]_e = [e]_e : T_1 \Rightarrow^l T_2$$

$$\frac{[c_1]_c = \varnothing\ T_1\ ^{n_1}\ \ \ldots\ \ [c_n]_c = \varnothing\ T_n\ ^{n_n}}{[e : c_1 \cap \ldots \cap c_n]_e = [e]_e}$$

$$\frac{[c_1]_c = c_1'\ \ \ldots\ \ [c_n]_c = c_n'}{[e : c_1 \cap \ldots \cap c_n]_e = [e]_e : c_1' \cap \ldots \cap c_n'}$$

$\boxed{[c]_c = \mathrm{c}}$ Erase identity casts

$$[c : T \Rightarrow^l T\ ^n]_c = [c]_c$$

$$[c : T_1 \Rightarrow^l T_2\ ^n]_c = [c]_c : T_1 \Rightarrow^l T_2\ ^n$$

$$[blame\ T_I\ T_F\ l\ ^n]_c = blame\ T_I\ T_F\ l\ ^n$$

$$[\varnothing\ T\ ^n]_c = \varnothing\ T\ ^n$$

Figure 8: Identity Cast Erasure

## 2 Proofs

**Theorem 1** (Conservative Extension)**.** *Depends on Lemma 1. If e is fully static and T is a static type, then* $\Gamma \vdash_{\cap S} e : T \iff \Gamma \vdash_{\cap G} e : T$.

*Proof.* First we will prove that if $\vdash_{\cap S} e : T$ then $\vdash_{\cap G} e : T$. We proceed by induction on the length of the derivation tree of $\vdash_{\cap S}$.

Base case:

- e $= x$. If $\Gamma \vdash_{\cap S} x : T_i$, then $x : T_1 \cap \ldots \cap T_n \in \Gamma$ such that $T_i \in \{T_1, \ldots, T_n\}$. Therefore, by rule $\cap E$ of $\vdash_{\cap G}$, $\Gamma \vdash_{\cap G} e : T_i$.

Induction step:

- e $= \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e'$. There are two possibilities:
  - Using the rule $\rightarrow I$. If $\Gamma \vdash_{\cap S} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_1 \cap \ldots \cap T_n \rightarrow T$, then $\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap S} e' : T$. By the induction hypothesis, $\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap G} e' : T$. Therefore, by rule $\rightarrow I$, $\Gamma \vdash_{\cap G} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_1 \cap \ldots \cap T_n \rightarrow T$.
  - Using the rule $\rightarrow I'$. If $\Gamma \vdash_{\cap S} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_i \rightarrow T$, then $\Gamma, x : T_i \vdash_{\cap S} e' : T$. By the induction hypothesis, $\Gamma, x : T_i \vdash_{\cap G} e' : T$. Therefore, by rule $\rightarrow I'$, $\Gamma \vdash_{\cap G} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_i \rightarrow T$.
- e $= e_1 \ e_2$. If $\Gamma \vdash_{\cap S} e_1 \ e_2 : T$ then $\Gamma \vdash_{\cap S} e_1 : T_1 \cap \ldots \cap T_n \rightarrow T$ and $\Gamma \vdash_{\cap S} e_2 : T_1 \cap \ldots \cap T_n$. By the induction hypothesis, $\Gamma \vdash_{\cap G} e_1 : T_1 \cap \ldots \cap T_n \rightarrow T$ and $\Gamma \vdash_{\cap G} e_2 : T_1 \cap \ldots \cap T_n$. By the definition of $\rhd$, $T_1 \cap \ldots \cap T_n \rightarrow T \rhd T_1 \cap \ldots \cap T_n \rightarrow T$. By the definition of consistency ($T \sim T$), $T_1 \cap \ldots \cap T_n \sim T_1 \cap \ldots \cap T_n$. Therefore, by rule $\rightarrow E$, $\Gamma \vdash_{\cap G} e_1 \ e_2 : T$.
- e $= e$. If $\Gamma \vdash_{\cap S} e : T_1 \cap \ldots \cap T_n$ then $\Gamma \vdash_{\cap S} e : T_1$ and ... and $\Gamma \vdash_{\cap S} e : T_n$. By the induction hypothesis, $\Gamma \vdash_{\cap G} e : T_1$ and ... and $\Gamma \vdash_{\cap G} e : T_n$. Therefore, by rule $\cap E$, $\Gamma \vdash_{\cap G} e : T_1 \cap \ldots \cap T_n$.

Now we will prove that if $\vdash_{\cap G} e : T$ then $\vdash_{\cap S} e : T$. We proceed by induction on the length of the derivation tree of $\vdash_{\cap G}$.

Base case:

- e $= x$. If $\Gamma \vdash_{\cap G} x : T_i$, then $x : T_1 \cap \ldots \cap T_n \in \Gamma$ such that $T_i \in \{T_1, \ldots, T_n\}$. Therefore, by rule $\cap E$ of $\vdash_{\cap S}$, $\Gamma \vdash_{\cap S} e : T_i$.

Induction step:

- e $= \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e'$. There are two possibilities:
  - Using the rule $\rightarrow I$. If $\Gamma \vdash_{\cap G} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_1 \cap \ldots \cap T_n \rightarrow T$, then $\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap G} e' : T$. By the induction hypothesis, $\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap S} e' : T$. Therefore, by rule $\rightarrow I$, $\Gamma \vdash_{\cap S} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_1 \cap \ldots \cap T_n \rightarrow T$.

  - Using the rule $\rightarrow I'$. If $\Gamma \vdash_{\cap G} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_i \rightarrow T$, then $\Gamma, x : T_i \vdash_{\cap G} e' : T$. By the induction hypothesis, $\Gamma, x : T_i \vdash_{\cap S} e' : T$. Therefore, by rule $\rightarrow I'$, $\Gamma \vdash_{\cap S} \lambda x \ . \ T_1 \cap \ldots \cap T_n \ . \ e' : T_i \rightarrow T$.

- e = $e_1 \ e_2$. If $\Gamma \vdash_{\cap G} e_1 \ e_2 : T$ then $\Gamma \vdash_{\cap G} e_1 : PM$, $PM \rhd T_1 \cap \ldots \cap T_n \rightarrow T$, $\Gamma \vdash_{\cap G} e_2 : T_1' \cap \ldots \cap T_n'$ and $T_1' \cap \ldots \cap T_n' \sim T_1 \cap \ldots \cap T_n$. By the definition of $\rhd$, $PM = T_1 \cap \ldots \cap T_n \rightarrow T$, therefore $\Gamma \vdash_{\cap G} e_1 : T_1 \cap \ldots \cap T_n \rightarrow T$. By Lemma 1, $T_1' \cap \ldots \cap T_n' = T_1 \cap \ldots \cap T_n$, and therefore $\Gamma \vdash_{\cap G} e_2 : T_1 \cap \ldots \cap T_n$. By the induction hypothesis, $\Gamma \vdash_{\cap S} e_1 \ : T_1 \cap \ldots \cap T_n \rightarrow T$ and $\Gamma \vdash_{\cap S} e_2 : T_1 \cap \ldots \cap T_n$. Therefore, by rule $\rightarrow E$, $\Gamma \vdash_{\cap S} e_1 \ e_2 : T$.

- e = $e$. If $\Gamma \vdash_{\cap G} e : T_1 \cap \ldots \cap T_n$ then $\Gamma \vdash_{\cap G} e : T_1$ and ... and $\Gamma \vdash_{\cap G} e : T_n$. By the induction hypothesis, $\Gamma \vdash_{\cap S} e : T_1$ and ... and $\Gamma \vdash_{\cap S} e : T_n$. Therefore, by rule $\cap E$, $\Gamma \vdash_{\cap S} e : T_1 \cap \ldots \cap T_n$.

□

**Theorem 2** (Conservative Extension)**.** *Depends on Lemmas 5 and 7. If $e$ is fully static, $T$ is a static type and $\Gamma \vdash_{\cap CC} e \rightsquigarrow e' : T$, then $e \longrightarrow_{\cap S} v \iff e' \longrightarrow_{\cap CC} v$.*

*Proof.* Since $\Gamma \vdash_{\cap CC} e \rightsquigarrow e' : T$ and $e$ is fully static, then by Lemma 5 and by the definition of $\Gamma \vdash_{\cap CC} e \rightsquigarrow e' : T$, the expression $e$ equals $e'$, except that $e'$ contains identity casts. Therefore, $[e']_e = e$. Then, by Lemma 7, if $e \longrightarrow v$ and $e' \longrightarrow_{\cap CC} v'$, then v = v'. □

**Theorem 3** (Monotonicity w.r.t. precision)**.** *If $\Gamma \vdash_{\cap G} e : T$ and $e' \sqsubseteq e$ then $\exists T' \ . \ \Gamma \vdash_{\cap G} e' : T'$ and $T' \sqsubseteq T$.*

*Proof.* We proceed by induction on the length of the derivation tree of $\Gamma \vdash_{\cap G} e : T$.

Base case:

- e = $x$. If $\Gamma \vdash_{\cap G} x : T_i$ and $x \sqsubseteq x$, then $\Gamma \vdash_{\cap G} x : T_i$ and $T_i \sqsubseteq T_i$.

- e = $n$. If $\Gamma \vdash_{\cap G} n : Int$ and $n \sqsubseteq n$, then $\Gamma \vdash_{\cap G} n : Int$ and $Int \sqsubseteq Int$.

- e = $true$. If $\Gamma \vdash_{\cap G} true : Bool$ and $true \sqsubseteq true$, then $\Gamma \vdash_{\cap G} true : Bool$ and $Bool \sqsubseteq Bool$.

- e = $false$. If $\Gamma \vdash_{\cap G} false : Bool$ and $false \sqsubseteq false$, then $\Gamma \vdash_{\cap G} false : Bool$ and $Bool \sqsubseteq Bool$.

Induction step:

- e = $\lambda x : T_1 \cap \ldots \cap T_n \ . \ e_1$. If $\Gamma \vdash_{\cap G} \lambda x : T_1 \ . \ e_1 : T_1 \rightarrow T_2$ and $\lambda x : T_1' \ . \ e_1' \sqsubseteq \lambda x : T_1 \ . \ e_1$, then $\Gamma \vdash_{\cap G} e_1 : T_2$, $T_1' \sqsubseteq T_1$ and $e_1' \sqsubseteq e_1$. By the induction hypothesis, $\exists T_2' \ . \ \Gamma \vdash_{\cap G} e_1' : T_2'$ *and* $T_2' \sqsubseteq T_2$. As $\Gamma \vdash_{\cap G} \lambda x : T_1' \ . \ e_1' : T_1' \rightarrow T_2'$, and by the definition of $\sqsubseteq$, $T_1' \rightarrow T_2' \sqsubseteq T_1 \rightarrow T_2$, then it is proved.

- e = $e_1\ e_2$. If $\Gamma \vdash_{\cap G} e_1\ e_2 : T$ and $e'_1\ e'_2 \sqsubseteq e_1\ e_2$ then $\Gamma \vdash_{\cap G} e_1 : PM$, $PM \rhd T_{11} \cap \ldots \cap T_{1n} \to T$, $\Gamma \vdash_{\cap G} e_2 : T_{21} \cap \ldots \cap T_{2n}$, and $T_{21} \cap \ldots \cap T_{2n} \sim T_{11} \cap \ldots \cap T_{1n}$, $e'_1 \sqsubseteq e_1$ and $e'_2 \sqsubseteq e_2$. By the induction hypothesis, $\exists PM' \,.\, \Gamma \vdash_{\cap G} e'_1 : PM'$ *and* $PM' \sqsubseteq PM$ *and* $PM' \rhd T'_{11} \cap \ldots \cap T'_{1n} \to T'$ and $\exists T'_{21}, \ldots, T'_{2n} \,.\, \Gamma \vdash_{\cap G} e'_2 : T'_{21} \cap \ldots \cap T'_{2n}$ *and* $T'_{21} \cap \ldots \cap T'_{2n} \sqsubseteq T_{21} \cap \ldots \cap T_{2n}$ *and* $T'_{21} \cap \ldots \cap T'_{2n} \sim T'_{11} \cap \ldots \cap T'_{1n}$. By the definition of $\sqsubseteq$ and $\rhd$, $T'_{11} \cap \ldots \cap T'_{1n} \to T' \sqsubseteq T_{11} \cap \ldots \cap T_{1n} \to T$, and therefore, $T' \sqsubseteq T$. As $\Gamma \vdash_{\cap G} e'_1\ e'_2 : T'$, it is proved.

- e = $e$. If $\Gamma \vdash_{\cap G} e : T_1 \cap \ldots \cap T_n$ and $e' \sqsubseteq e$, then $\Gamma \vdash_{\cap G} e : T_1$ and ... and $\Gamma \vdash_{\cap G} e : T_n$. By the induction hypothesis, $\exists T'_1 \,.\, \Gamma \vdash_{\cap G} e' : T'_1$ *and* $T'_1 \sqsubseteq T_1$ and ... and $\exists T'_n \,.\, \Gamma \vdash_{\cap G} e' : T'_n$ *and* $T'_n \sqsubseteq T_n$. Then, $\Gamma \vdash_{\cap G} e' : T'_1 \cap \ldots \cap T'_n$ and by the definition of $\sqsubseteq$, $T'_1 \cap \ldots \cap T'_n \sqsubseteq T_1 \cap \ldots \cap T_n$, then it is proved.

$\square$

**Theorem 4** (Subject reduction of $\longrightarrow_{\cap CC}$)**.** *Depends on Lemmas 2 and 3. If* $\Gamma \vdash_{\cap CC} e : T$ *and* $e \longrightarrow_{\cap CC} e'$ *then* $\Gamma \vdash_{\cap CC} e' : T$.

*Proof.* We proceed by induction on the length of the derivation tree of $\vdash_{\cap S}$.

Base case:

- e = $v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2$ and $isValue\ v : cv_1 \cap \ldots \cap cv_n$ and $v : c'_1 \cap \ldots \cap c'_m = mergeIC(v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2)$. If $\Gamma \vdash_{\cap CC} v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2 : T_2$ then $\Gamma \vdash_{\cap CC} v : cv_1 \cap \ldots \cap cv_n : T_1 \cap \ldots \cap T_1$ and $T_1 \cap \ldots \cap T_1 =_\cap T_1$ and $\vdash_{\cap IC} cv_1 : T_1$ and $I_1 = initialType(cv_1)$ and ... and $\vdash_{\cap IC} cv_n : T_1$ and $I_n = initialType(cv_n)$ and $\Gamma \vdash_{\cap CC} v : I_1 \cap \ldots \cap I_n$. By the definition of mergeIC, $mergeIC(v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2) = v : (cv_1 : T_1 \Rightarrow^l T_2\ {}^{m_1}) \cap \ldots \cap (cv_n : T_1 \Rightarrow^l T_2\ {}^{m_n})$. As $\Gamma \vdash_{\cap CC} v : (cv_1 : T_1 \Rightarrow^l T_2\ {}^{m_1}) \cap \ldots \cap (cv_n : T_1 \Rightarrow^l T_2\ {}^{m_n}) : T_2 \cap \ldots \cap T_2$ and $T_2 \cap \ldots \cap T_2 =_\cap T_2$ and by rule MergeIC$\cap$, $v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2 \longrightarrow_{\cap CC} v : (cv_1 : T_1 \Rightarrow^l T_2\ {}^{m_1}) \cap \ldots \cap (cv_n : T_1 \Rightarrow^l T_2\ {}^{m_n})$, then it is proved.

- e = $v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n$ and $isValue\ v : T_1 \Rightarrow^l T_2$ and $v : c'_1 \cap \ldots \cap c'_m = mergeCI(v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n)$. If $\Gamma \vdash_{\cap CC} v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n : F_1 \cap \ldots \cap F_n$ then $\Gamma \vdash_{\cap CC} v : T_1 \Rightarrow T_2 : T_2$ and $\Gamma \vdash_{\cap CC} v : T_1$ and $\vdash_{\cap IC} c_1 : F_1$ and $initialType(c_1) : T_2$ and ... and $\vdash_{\cap IC} c_n : F_n$ and $initialType(c_n) : T_2$. By the definition of mergeCI, $mergeCI(v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n) = v : c'_1 \cap \ldots \cap c'_n$, such that $\vdash_{\cap IC} c'_1 : F_1$ and $initialType(c'_1) : T_1$ and ... and $\vdash_{\cap IC} c'_n : F_n$ and $initialType(c'_n) : T_1$. As $\Gamma \vdash_{\cap CC} v : c'_1 \cap \ldots \cap c'_n : F_1 \cap \ldots \cap F_n$ and by rule MergeCI$\cap$, $v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n \longrightarrow_{\cap CC} v : c'_1 \cap \ldots \cap c'_n$, then it is proved.

- e = $v : c_1 \cap \ldots \cap c_n$ and $\neg(\forall i \in 1..n \,.\, isCastValue\ c_i)$. If $\Gamma \vdash_{\cap CC} v : c_1 \cap \ldots \cap c_n : T_1 \cap \ldots \cap T_n$ then $\vdash_{\cap IC} c_1 : T_1$ and ... and $\vdash_{\cap IC} c_n : T_n$, $\Gamma \vdash_{\cap CC} v : I_1 \cap \ldots \cap I_n$, with $I_1 = initialType(c_1)$ and ... and $I_n = initialType(c_n)$. By rule Evaluate$\cap$, $c_1 \longrightarrow_{\cap IC} cv_1$ and ... and $c_n \longrightarrow_{\cap IC} cv_n$. By Lemmas 2 and 3, $\vdash_{\cap IC} cv_1 : T_1$ and ... and $\vdash_{\cap IC} cv_n : T_n$

and $initialType(cv_1) = I_1$ and ... and $initialType(cv_n) = I_n$. Therefore $\Gamma \vdash_{\cap CC} v : cv_1 \cap \ldots \cap cv_n : T_1 \cap \ldots \cap T_n$.

- e $= v : blame\ T_1'\ T_1\ l_1\ ^{m_1} \cap \ldots \cap blame\ T_n'\ T_n\ l_n\ ^{m_n}$. If $\Gamma \vdash_{\cap CC} v : blame\ T_1'\ T_1\ l_1\ ^{m_1} \cap \ldots \cap blame\ T_n'\ T_n\ l_n\ ^{m_n} : T_1 \cap \ldots \cap T_n$ and by rule PropagateBlame$\cap$ $v : blame\ T_1'\ T_1\ l_1\ ^{m_1} \cap \ldots \cap blame\ T_n'\ T_n\ l_n\ ^{m_n} \longrightarrow_{\cap CC} blame_{(T_1 \cap \ldots \cap T_n)}\ l_1$, and $\Gamma \vdash_{\cap CC} blame_{(T_1 \cap \ldots \cap T_n)}\ l_1 : T_1 \cap \ldots \cap T_n$, then it is proved.

- e $= v : \varnothing\ T_1\ ^{m_1} \cap \ldots \cap \varnothing\ T_n\ ^{m_n}$. If $\Gamma \vdash_{\cap CC} v : \varnothing\ T_1\ ^{m_1} \cap \ldots \cap \varnothing\ T_n\ ^{m_n} : T_1 \cap \ldots \cap T_n$, then $\vdash_{\cap IC} \varnothing\ T_1\ ^{m_1} : T_1$ and $initialType(\varnothing\ T_1\ ^{m_1}) = T_1$ and ... and $\vdash_{\cap IC} \varnothing\ T_n\ ^{m_n} : T_n$ and $initialType(\varnothing\ T_n\ ^{m_n}) = T_n$ and $\Gamma \vdash_{\cap CC} v : T_1 \cap \ldots \cap T_n$. By rule RemoveEmpty$\cap$, $v : \varnothing\ T_1\ ^{m_1} \cap \ldots \cap \varnothing\ T_n\ ^{m_n} \longrightarrow_{\cap CC} v$, therefore it is proved.

Induction step:

- e $=$

$\square$

**Lemma 1** (Consistency reduces to equality when comparing static types)**.** *If $T_1$ and $T_2$ are static types then $T_1 = T_2 \iff T_1 \sim T_2$.*

*Proof.* We proceed by structural induction on $T$.

Base cases:

- $T_1 = Int$.
  - If $T_1 = T_2$, then by the definition of $\sim$, $T_1 \sim T_2$.
  - If $T_1 \sim T_2$, then by the definition of $\sim$, $T_1 = T_2$.
- $T_1 = Bool$.
  - If $T_1 = T_2$, then by the definition of $\sim$, $T_1 \sim T_2$.
  - If $T_1 \sim T_2$, then by the definition of $\sim$, $T_1 = T_2$.
- $T_1 = Dyn$. This case is not considered due to the assumption that $T_1$ is a static type.

Induction step:

- $T_1 = T_{11} \rightarrow T_{12}$.
  - If $T_1 = T_2$, then $\exists T_{21}, T_{22}\ .\ T_2 = T_{21} \rightarrow T_{22}$ and $T_{11} = T_{21}$ and $T_{12} = T_{22}$. By the induction hypothesis, $T_{11} \sim T_{21}$ and $T_{12} \sim T_{22}$. Therefore, by the definition of $\sim$, $T_1 \sim T_2$.
  - If $T_1 \sim T_2$, then $\exists T_{21}, T_{22}\ .\ T_2 = T_{21} \rightarrow T_{22}$ and $T_{11} = T_{21}$ and $T_{12} = T_{22}$. By the induction hypothesis, $T_{11} = T_{21}$ and $T_{12} = T_{22}$. Therefore, by the definition of $=$, $T_1 = T_2$.
- $T_1 = T_{11} \cap \ldots \cap T_{1n}$.

– If $T_1 = T_2$, then $\exists T_{21}, \ldots, T_{2n} \,.\, T_2 = T_{21} \cap \ldots \cap T_{2n}$ and $T_{11} = T_{21}$ and ... and $T_{1n} = T_{2n}$. By the induction hypothesis, $T_{11} \sim T_{21}$ and ... and $T_{1n} \sim T_{2n}$. Therefore, by the definition of $\sim$, $T_1 \sim T_2$.

– If $T_1 \sim T_2$, then $\exists T_{21}, \ldots, T_{2n} \,.\, T_2 = T_{21} \cap \ldots \cap T_{2n}$ and $T_{11} \sim T_{21}$ and ... and $T_{1n} \sim T_{2n}$. By the induction hypothesis, $T_{11} = T_{21}$ and ... and $T_{1n} = T_{2n}$. Therefore, by the definition of $=$, $T_1 = T_2$.

$\square$

**Lemma 2** (Subject reduction of $\longrightarrow_{\cap IC}$). *If $\vdash_{\cap IC} c : T$ for some $T$ and $c \longrightarrow_{\cap IC} c'$ then $\vdash_{\cap IC} c' : T$.*

*Proof.* We proceed by induction on the length of the derivation tree of $\longrightarrow_{\cap IC}$.

Base cases:

- c $=$ $blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2}$. $\vdash_{\cap IC} blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2} : T_2$ and by rule PushBlameC, $blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ T_2\ l_1\ ^{n_1}$. As $\vdash_{\cap IC} blame\ T_I\ T_2\ l_1\ ^{n_1} : T_2$, then it is proved.

- c $=$ $c' : T \Rightarrow^l T\ ^n$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$. If $\vdash_{\cap IC} c' : T \Rightarrow^l T\ ^n : T$, then $\vdash_{\cap IC} c' : T$. By rule IdentityC, $c' : T \Rightarrow^l T\ ^n \longrightarrow_{\cap IC} c'$. Therefore it is proved.

- c $=$ $c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2}$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$. If $\vdash_{\cap IC} c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2} : G$, then $\vdash_{\cap IC} c' : G$. By rule SucceedC, $c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2} \longrightarrow_{\cap IC} c'$. Therefore it is proved.

- c $=$ $c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2}$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$ and $\neg(same\ ground\ G_1\ G_2)$ and $initialType(c') = T_I$. If $\vdash_{\cap IC} c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2} : G_2$, and by rule FailC, $c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ G_2\ l_2\ ^{n_1}$ and $\vdash_{\cap IC} blame\ T_I\ G_2\ l_2\ ^{n_1} : G_2$, it is proved.

- c $=$ $c' : T \Rightarrow^l Dyn\ ^n$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$ and $G\ is\ ground\ type\ of\ T$ and $\neg(ground\ T)$. If $\vdash_{\cap IC} c' : T \Rightarrow^l Dyn\ ^n : Dyn$ then $\vdash_{\cap IC} c' : T$. By rule GroundC, $c' : T \Rightarrow^l Dyn\ ^n \longrightarrow_{\cap IC} c' : T \Rightarrow^l G\ ^n : G \Rightarrow^l Dyn\ ^n$. As $\vdash_{\cap IC} c' : T \Rightarrow^l G\ ^n : G \Rightarrow^l Dyn\ ^n : Dyn$, it is proved.

- c $=$ $c' : Dyn \Rightarrow^l T\ ^n$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$ and $G\ is\ ground\ type\ of\ T$ and $\neg(ground\ T)$. If $\vdash_{\cap IC} c' : Dyn \Rightarrow^l T\ ^n : T$ then $\vdash_{\cap IC} c' : Dyn$. By rule ExpandC, $c' : Dyn \Rightarrow^l T\ ^n \longrightarrow_{\cap IC} c' : Dyn \Rightarrow^l G\ ^n : G \Rightarrow^l T\ ^n$. As $\vdash_{\cap IC} c' : Dyn \Rightarrow^l G\ ^n : G \Rightarrow^l T\ ^n : T$, it is proved.

Induction step:

- c $=$ $c' : T_1 \Rightarrow^l T_2\ ^n$ and $\neg(isCastValue\ c)$. If $\vdash_{\cap IC} c' : T_1 \Rightarrow^l T_2\ ^n : T_2$ then $\vdash_{\cap IC} c' : T_1$. By rule EvaluateC, $c' \longrightarrow_{\cap IC} c''$. By the induction hypothesis, $\vdash_{\cap IC} c'' : T_1$. By rule EvaluateC, $c' : T_1 \Rightarrow^l T_2\ ^n \longrightarrow_{\cap IC} c'' : T_1 \Rightarrow^l T_2\ ^n$. As $\vdash_{\cap IC} c'' : T_1 \Rightarrow^l T_2\ ^n : T_2$ it is proved.

$\square$

**Lemma 3** (Initial type preservation of $\longrightarrow_{\cap IC}$)**.** *If $initialType(c) = T$ for some $T$ and $c \longrightarrow_{\cap IC} c'$ then $initialType(c') = T$.*

*Proof.* We proceed by induction on the length of the derivation tree of $\longrightarrow_{\cap IC}$.

Base cases:

- c $= blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2}$. By the definition of $initialType$, $initialType(blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2}) = T_I$. By rule PushBlameC, $blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ T_2\ l_1\ ^{n_1}$. Since $initialType(blame\ T_I\ T_2\ l_1\ ^{n_1}) = T_I$, it is proved.

- c $= c' : T \Rightarrow^l T\ ^n$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$. By the definitions of $initialType$, $initialType(c' : T \Rightarrow^l T\ ^n) = initialType(c')$. By rule IdentityC, $c' : T \Rightarrow^l T\ ^n \longrightarrow_{\cap IC} c'$. Therefore it is proved.

- c $= c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2}$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$. By the definition of $initialType$, $initialType(c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2}) = initialType(c')$. By rule SucceedC, $c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2} \longrightarrow_{\cap IC} c'$. Therefore it is proved.

- c $= c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2}$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$ and $\neg(same\ ground\ G_1\ G_2)$ and $initialType(c') = T_I$. By the definition of $initialType$, $initialType(c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2}) = T_I$. By rule FailC, $c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ G_2\ l_2\ ^{n_1}$. Since $initialType(blame\ T_I\ G_2\ l_2\ ^{n_1}) = T_I$, it is proved.

- c $= c' : T \Rightarrow^l Dyn\ ^n$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$ and $G\ is\ ground\ type\ of\ T$ and $\neg(ground\ T)$. By the definition of $initialType$, $initialType(c' : T \Rightarrow^l Dyn\ ^n) = initialType(c')$. By rule GroundC, $c' : T \Rightarrow^l Dyn\ ^n \longrightarrow_{\cap IC} c' : T \Rightarrow^l G\ ^n : G \Rightarrow^l Dyn\ ^n$. Since $initialType(c' : T \Rightarrow^l G\ ^n : G \Rightarrow^l Dyn\ ^n) = initialType(c')$, it is proved.

- c $= c' : Dyn \Rightarrow^l T\ ^n$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$ and $G\ is\ ground\ type\ of\ T$ and $\neg(ground\ T)$. By the definition of $initialType$, $initialType(c' : Dyn \Rightarrow^l T\ ^n) = initialType(c')$. By rule ExpandC, $c' : Dyn \Rightarrow^l T\ ^n \longrightarrow_{\cap IC} c' : Dyn \Rightarrow^l G\ ^n : G \Rightarrow^l T\ ^n$. Since $initialType(c' : Dyn \Rightarrow^l G\ ^n : G \Rightarrow^l T\ ^n) = initialType(c')$, it is proved.

Induction step:

- c $= c' : T_1 \Rightarrow^l T_2\ ^n$ and $\neg(isCastValue\ c')$. By the definition of $initialType$, $initialType(c' : T_1 \Rightarrow^l T_2\ ^n) = initialType(c')$. By rule EvaluateC, $c' \longrightarrow_{\cap IC} c''$. By the induction hypothesis, $initialType(c'') = initialType(c')$. By rule EvaluateC, $c' : T_1 \Rightarrow^l T_2\ ^n \longrightarrow_{\cap IC} c'' : T_1 \Rightarrow^l T_2\ ^n$. Since $initialType(c'' : T_1 \Rightarrow^l T_2\ ^n) = initialType(c'')$, it is proved.

$\square$

**Lemma 4** (Expressions annotated with only static types type with static types)**.** *If $e$ is annotated with only static types then:*

1. $\Gamma \vdash_{\cap G} e : T$, *for some static* $T$.

2. $\Gamma \vdash_{\cap CC} e \rightsquigarrow e' : T$, *for some static* $T$.

*Proof.* (1) We proceed by induction on the length of the derivation tree of $\vdash_{\cap G}$.

Base cases:

- e $= x$. If $\Gamma \vdash_{\cap G} x : T_i$, then there is a binding $x : T' \in \Gamma$, such that $T_i \subseteq T'$. Therefore, there must have been at some point in the typing derivation, the application of the rules $(\rightarrow I)$ or $(\rightarrow I')$. If $e$ is annotated with only static types, then both rules introduze the binding $x : T'$ in $\Gamma$, such that $T'$ is a static type. Therefore, $T_i$ is also a static type.

Induction step:

- e $= \lambda x : T_1 \cap \ldots \cap T_n \; . \; e'$. There are two possibilities:
  - Using the rule $\rightarrow I$. If $e$ is annotated with only static types, then $T_1 \cap \ldots \cap T_n$ is a static type. By rule $(\rightarrow I)$, $\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap G} e : T$. By the induction hypothesis, $T$ is a static type. Therefore $T_1 \cap \ldots \cap T_n \rightarrow T$ is a static type.
  - Using the rule $\rightarrow I'$. If $e$ is annotated with only static types, then $T_1 \cap \ldots \cap T_n$ is a static type. By rule $(\rightarrow I')$, $\Gamma, x : T_i \vdash_{\cap G} e : T$. Since $T_1 \cap \ldots \cap T_n$ is a static type, then so is $T_i$. By the induction hypothesis, $T$ is a static type, therefore so is $T_i \rightarrow T$.
- e $= e_1 \; e_2$. If $e$ is annotated with only static types, then so are $e_1$ and $e_2$. By the induction hypothesis, $PM$ is a static type. By the definition of $\rhd$, $T_1 \cap \ldots \cap T_n \rightarrow T$ is also a static type. Therefore, $T$ is a static type.
- e $= e$. If $e$ annotated with only static types, then by the induction hypothesis, $T_1 \ldots T_n$ are static types. Therefore $T_1 \cap \ldots \cap T_n$ is a static type.

(2) We proceed by induction on the length of the derivation tree of $\Gamma \vdash_{\cap CC} e \rightsquigarrow e : T$.

Base cases:

- e $= x$. If $\Gamma \vdash_{\cap CC} x \rightsquigarrow x : T_i$, then there is a binding $x : T' \in \Gamma$, such that $T_i \subseteq T'$. Therefore, there must have been at some point in the typing derivation, the application of the rule for the term $\lambda x : T_1 \cap \ldots \cap T_n \; . \; e'$. If $e$ is annotated with only static types, then the rule introduzes the binding $x : T'$ in $\Gamma$, such that $T'$ is a static type. Therefore, $T_i$ is also a static type.

Induction step:

- e $= \lambda x : T_1 \cap \ldots \cap T_n \; . \; e'$. If $e$ is annotated with only static types, then $T_1 \cap \ldots \cap T_n$ is a static type. By the induction hypothesis, $T$ is a static type. Therefore $T_1 \cap \ldots \cap T_n \rightarrow T$ is a static type.

- e $= e_1\ e_2$. If $e$ is annotated with only static types, then so are $e_1$ and $e_2$. By the induction hypothesis, $PM$ is a static type. By the definition of $\triangleright$, $T_1 \cap \ldots \cap T_n \to T$ is also a static type. Therefore, $T$ is a static type.

$\square$

**Lemma 5** (Static program compilation only adds identity casts)**.** *Depends on Lemmas 1 and 4. If e is annotated with only static types and* $\Gamma \vdash_{\cap CC} e \rightsquigarrow e' : T$, *then any casts* $e'$ *contains are identity casts.*
*By identity casts, we mean casts of the form* $e : T \Rightarrow^l T$ *for some* $T$ *and casts* $e : c_1 \cap \ldots \cap c_n$ *such that* $c_1 = \varnothing\ T_1\ ^0 : T_1 \Rightarrow T_1\ ^0$ *and ... and* $c_n = \varnothing\ T_n\ ^0 : T_n \Rightarrow T_n\ ^0$ *for some* $T_1,\ \ldots,\ T_n$.

*Proof.* We proceed by structural induction on $e$.

Base cases:

- e $= x$. As $\Gamma \vdash_{\cap CC} x \rightsquigarrow x : T_i$, and $x$ doesn't have any casts, then it is proved.

Induction step:

- e $= \lambda x : T_1 \cap \ldots \cap T_n\ .\ e'$. By rule, $\Gamma \vdash_{\cap CC} e' \rightsquigarrow e'' : T$. By the induction hypothesis, $e''$ either doesn't contain casts or contains only identity casts. By rule, $\Gamma \vdash_{\cap CC} (\lambda x : T_1 \cap \ldots \cap T_n\ .\ e') \rightsquigarrow (\lambda x : T_1 \cap \ldots \cap T_n\ .\ e'') : T_1 \cap \ldots \cap T_n \to T$. As the rule doesn't introduze new casts, then it is proved.
- e $= e_1\ e_2$. By rule, $\Gamma \vdash_{\cap CC} e_1 \rightsquigarrow e_1' : PM$ and $\Gamma \vdash_{\cap CC} e_2 \rightsquigarrow e_2' : T_1' \cap \ldots \cap T_n'$. By the induction hypothesis, both $e_1'$ as well as $e_2'$ either only have identity casts or no casts at all. By Lemma 4, $PM$ and $T_1' \cap \ldots \cap T_n'$ are static types. Therefore, by the definition of $\triangleright$, $PM = T_1' \cap \ldots \cap T_n' \to T$ and by Lemma 1, $T_1' \cap \ldots \cap T_n' = T_1 \cap \ldots \cap T_n$. Therefore by the definition of *getInstances* and *addCasts*, only identity casts are introduzed.

$\square$

**Lemma 6** (Elimination of identity casts in c)**.** *For any cast c, such that* $\vdash_{\cap IC} c : T_F$, *initialType*$(c) = T_I$ *and* $c \longrightarrow_{\cap IC} cv$*:*

1. $\vdash_{\cap IC} [c]_c : T_F$ *and initialType*$([c]_c) = T_I$.
2. $[c]_c \longrightarrow_{\cap IC} cv$.

*Proof.* (1) We proceed by structural induction on $c$.

Base cases:

- c $= \varnothing\ T\ ^n$. As $\vdash_{\cap IC} \varnothing\ T\ ^n : T$, *initialType*$(\varnothing\ T\ ^n) = T$ and $[c]_c = \varnothing\ T\ ^n$, then $\vdash_{\cap IC} [c]_c : T$ and *initialType*$([c]_c) = T$.
- c $=$ *blame* $T_I\ T_F\ l\ ^n$. As $\vdash_{\cap IC}$ *blame* $T_I\ T_F\ l\ ^n : T_F$, *initialType*(*blame* $T_I\ T_F\ l\ ^n) = T_I$ and $[c]_c =$ *blame* $T_I\ T_F\ l\ ^n$, then $\vdash_{\cap IC} [c]_c : T_F$ and *initialType*$([c]_c) = T_I$.

Induction step:

- c $= c' : T_1 \Rightarrow^l T_2\ ^n$. There are two cases:
  - $T_1 \neq T_2$. As $\vdash_{\cap IC} c' : T_1 \Rightarrow^l T_2\ ^n : T_2$ and $initialType(c' : T_1 \Rightarrow^l T_2\ ^n) = initialType(c')$, then $\vdash_{\cap IC} c' : T_1$. By the induction hypothesis, $\vdash_{\cap IC} [c']_c : T_1$ and $initialType([c']_c) = initialType(c')$. With $[c]_c = [c']_c : T_1 \Rightarrow^l T_2\ ^n$, $\vdash_{\cap IC} [c]_c : T_2$ and $initialType([c]_c) = initialType([c']_c) = initialType(c') = initialType(c)$.
  - $T_1 = T_2$. As $\vdash_{\cap IC} c' : T_1 \Rightarrow^l T_1\ ^n : T_1$ and $initialType(c' : T_1 \Rightarrow^l T_1\ ^n) = initialType(c')$ then $\vdash_{\cap IC} c' : T_1$. By the induction hypothesis, $\vdash_{\cap IC} [c']_c : T_1$ and $initialType([c']_c) = initialType(c')$. With $[c]_c = [c']_c$, $\vdash_{\cap IC} [c]_c : T_1$ and $initialType([c]_c) = initialType([c']_c) = initialType(c') = initialType(c)$.

(2) We proceed by structural induction on $c$.

Base cases:

- c $= blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2}$. There are two cases:
  - $T_1 \neq T_2$. As $[c]_c = blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2}$ and by rule Push-BlameC, $blame\ T_I\ T_F\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_2\ ^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ T_2\ l_1\ ^{n_1}$ it is proved.
  - $T_1 = T_2$. If $T_1 = T_2$, then by rules T-SingleC and T-BlameC, $T_F = T_1$. Therefore, $c = blame\ T_I\ T_1\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_1\ ^{n_2}$. By rule Push-BlameC, $blame\ T_I\ T_1\ l_1\ ^{n_1} : T_1 \Rightarrow^{l_2} T_1\ ^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ T_1\ l_1\ ^{n_1}$. Since $[c]_c = blame\ T_I\ T_1\ l_1\ ^{n_1}$, and it is already a value, it is proved.
- c $= c' : T \Rightarrow^l T\ ^n$ and $isCastValue1\ c' \vee isEmptyCast\ c'$. By rule IdentityC, $c' : T \Rightarrow^l T\ ^n \longrightarrow_{\cap IC} c'$. As $c'$ is a value, it doesn't contain identity casts, therefore $[c]_c = c'$. As $[c]_c$ is already a value, it reduces to itself, therefore it is proved.
- c $= c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2}$ and $isCastValue1\ c' \vee isEmptyCast\ c'$. By rule SucceedC, $c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2} \longrightarrow_{\cap IC} c'$. As $c'$ is already a value, then it doesn't contain identity casts, so $[c]_c = c' : G \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G\ ^{n_2}$. Therefore, $[c]_c \longrightarrow_{\cap IC} c'$.
- c $= c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2}$ and $isCastValue1\ c' \vee isEmptyCast\ c'$ and $\neg(same\ ground\ G_1\ G_2)$ and $initialType(c') = T_I$. By rule FailC, $c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2} \longrightarrow_{\cap IC} blame\ T_I\ G_2\ l_2\ ^{n_1}$. As $c'$ is already a value, then it doesn't contain identity casts, so $[c]_c = c' : G_1 \Rightarrow^{l_1} Dyn\ ^{n_1} : Dyn \Rightarrow^{l_2} G_2\ ^{n_2}$. Therefore, $[c]_c \longrightarrow_{\cap IC} blame\ T_I\ G_2\ l_2\ ^{n_1}$.
- c $= c' : T \Rightarrow^l Dyn\ ^n$ and $isCastValue1\ c' \vee isEmptyCast\ c'$ and $G\ is\ ground\ type\ of\ T$ and $\neg(ground\ T)$. By rule GroundC, $c' : T \Rightarrow^l Dyn\ ^n \longrightarrow_{\cap IC} c' : T \Rightarrow^l G : G \Rightarrow^l Dyn\ ^n$. As $c'$ is a value, it doesn't contain identity casts, therefore $[c]_c = c' : T \Rightarrow^l Dyn\ ^n$. Therefore $[c]_c \longrightarrow_{\cap IC} c' : T \Rightarrow^l G : G \Rightarrow^l Dyn\ ^n$.

- c $= c' : Dyn \Rightarrow^l T\ ^n$ and $isCastValue1\ c' \ \vee\ isEmptyCast\ c'$ and $G\ is\ ground\ type\ of\ T$ and $\neg(ground\ T)$. By rule ExpandC, $c' : Dyn \Rightarrow^l T\ ^n \longrightarrow_{\cap IC} c' : Dyn \Rightarrow^l G : G \Rightarrow^l T\ ^n$. As $c'$ is a value, it doesn't contain identity casts, therefore $[c]_c = c' : Dyn \Rightarrow^l T\ ^n$. Therefore $[c]_c \longrightarrow_{\cap IC} c' : Dyn \Rightarrow^l G : G \Rightarrow^l T\ ^n$.

Induction step:

- c $= c' : T_1 \Rightarrow^l T_2\ ^n$ and $\neg(isCastValuec')$. There are two cases:
  - $T_1 \neq T_2$. By rule EvaluateC, $c' \longrightarrow_{\cap IC} c''$. By the induction hypothesis, $[c']_c \longrightarrow_{\cap IC} c''$. As $[c]_c$ equals $[c']_c : T_1 \Rightarrow^l T_2\ ^n$, then by rule EvaluateC, $[c]_c \longrightarrow_{\cap IC} c'' : T_1 \Rightarrow T_2\ ^n$.
  - $T_1 = T_2$. By the induction hypothesis, as $c' \longrightarrow_{\cap IC} cv'$, then $[c']_c \longrightarrow_{\cap IC} cv'$. By rule EvaluateC, $c' : T_1 \Rightarrow^l T_1\ ^n \longrightarrow_{\cap IC} cv' : T_1 \Rightarrow^l T_1\ ^n$. However, as $cv' : T_1 \Rightarrow^l T_1\ ^n$ is not a value, the rule IdentityC must be applied, therefore $c' : T_1 \Rightarrow^l T_1\ ^n \longrightarrow_{\cap IC} cv'$. As $[c]_c \longrightarrow_{\cap IC} cv'$, then it is proved.

□

**Lemma 7** (Elimination of identity casts in e)**.** *Depends on Lemma 6. For any expression e, such that $\Gamma \vdash_{\cap CC} e : T$, and $e \longrightarrow_{\cap CC} v$:*

1. $\Gamma \vdash_{\cap CC} [e]_e : T$.
2. $[e]_e \longrightarrow_{\cap CC} v$.

*Proof.* (1) We proceed by induction on the length of the derivation tree of $\Gamma \vdash_{\cap CC} e : T$.

Base cases:

- e $= x$. As $x$ doesn't contain casts, then $[e]_e = x$. Therefore it is proved.
- e $= n$. As $n$ doesn't contain casts, then $[e]_e = n$. Therefore it is proved.
- e $= true$. As $true$ doesn't contain casts, then $[e]_e = true$. Therefore it is proved.
- e $= false$. As $false$ doesn't contain casts, then $[e]_e = false$. Therefore it is proved.
- e $= blame_T\ l$. As $blameTl$ doesn't contain casts, then $[e]_e = blameTl$. Therefore it is proved.

Induction step:

- e $= \lambda x : T_1 \cap \ldots \cap T_n\ .\ e'$. There are two possibilities:
  - Using the rule $\rightarrow I$. If $\Gamma \vdash_{\cap CC} \lambda x : T_1 \cap \ldots \cap T_n\ .\ e' : T_1 \cap \ldots \cap T_n \rightarrow T$, then $\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap CC} e' : T$. By the induction hypothesis, $\Gamma, x : T_1 \cap \ldots \cap T_n \vdash_{\cap CC} [e']_e : T$. As $[e]_e = \lambda x : T_1 \cap \ldots \cap T_n\ .\ [e']_e$, then $\Gamma \vdash_{\cap CC} [e]_e : T_1 \cap \ldots \cap T_n \rightarrow T$.

  - Using the rule $\to I'$. If $\Gamma \vdash_{\cap CC} \lambda x : T_1 \cap \ldots \cap T_n \, . \, e' : T_i \to T$, then $\Gamma, x : T_i \vdash_{\cap CC} e' : T$. By the induction hypothesis, $\Gamma, x : T_i \vdash_{\cap CC} [e']_e : T$. As $[e]_e = \lambda x : T_1 \cap \ldots \cap T_n \, . \, [e']_e$, then $\Gamma \vdash_{\cap CC} [e]_e : T_i \to T$.

- e $= e_1\ e_2$. If $\Gamma \vdash_{\cap CC} e_1\ e_2 : T$, then $\Gamma \vdash_{\cap CC} e_1 : PM$, $PM \rhd T_1 \cap \ldots \cap T_n \to T$, $\Gamma \vdash_{\cap CC} e_2 : T_1' \cap \ldots \cap T_n'$ and $T_1' \cap \ldots \cap T_n' \sim T_1 \cap \ldots \cap T_n$. By the induction hypothesis, $\Gamma \vdash_{\cap CC} [e_1]_e : PM$ and $\Gamma \vdash_{\cap CC} [e_2]_e : T_1' \cap \ldots \cap T_n'$. As $[e]_e = [e_1]_e\ [e_2]_e$, therefore $\Gamma \vdash_{\cap CC} [e]_e : T$.

- e $= e$. If $\Gamma \vdash_{\cap CC} e : T_1 \cap \ldots \cap T_n$, then $\Gamma \vdash_{\cap CC} e : T_1$ and ... and $\Gamma \vdash_{\cap CC} e : T_n$. By the induction hypothesis, $\Gamma \vdash_{\cap CC} [e]_e : T_1$ and ... and $\Gamma \vdash_{\cap CC} [e]_e : T_n$. Therefore $\Gamma \vdash_{\cap CC} [e]_e : T_1 \cap \ldots \cap T_n$.

- e $= e' : T_1 \Rightarrow^l T_2$. There are two possibilities:

  - $T_1 \neq T_2$. If $\Gamma \vdash_{\cap CC} e' : T_1 \Rightarrow^l T_2 : T_2$, then $\Gamma \vdash_{\cap CC} e' : T_1$. By the induction hypothesis, $\Gamma \vdash_{\cap CC} [e']_e : T_1$. As $[e]_e = [e']_e : T_1 \Rightarrow^l T_2$, then $\Gamma \vdash_{\cap CC} [e]_e : T_2$.
  - $T_1 = T_2$. If $\Gamma \vdash_{\cap CC} e' : T_1 \Rightarrow^l T_1 : T_1$, then $\Gamma \vdash_{\cap CC} e' : T_1$. By the induction hypothesis, $\Gamma \vdash_{\cap CC} [e']_e : T_1$. As $[e]_e = [e']_e : T_1 \Rightarrow^l T_1$, then $\Gamma \vdash_{\cap CC} [e]_e : T_1$.

- e $= e' : c_1 \cap \ldots \cap c_n$. If $\Gamma \vdash_{\cap CC} e' : c_1 \cap \ldots \cap c_n : T_1 \cap \ldots \cap T_n$, then $\Gamma \vdash_{\cap CC} e' : T$, $\vdash_{\cap IC} c_1 : T_1$ and ... and $\vdash_{\cap IC} c_n : T_n$ and $\mathit{initialType}(c_1) \cap \ldots \cap \mathit{initialType}(c_n) =_\cap T$. By the induction hypothesis, $\Gamma \vdash_{\cap CC} [e']_e : T$. We now have 2 possibilities:

  - $\neg(\forall i \in 1..n \, . \, \mathit{isEmptyCast}\ [c_i]_c)$: For all casts $c_i$, with $i \in 1..n$, that don't contain identity casts, then $[c_i]_c = c_i$, therefore $\vdash_{\cap IC} [c_i]_c : T_i$ and $\mathit{initialType}([c_i]_c) = \mathit{initialType}(c_i)$. For the remaining casts, by Lemma 6, $\vdash_{\cap IC} [c_i]_c : T_i$ and $\mathit{initialType}([c_i]_c) = \mathit{initialType}(c_i)$. Therefore, with $[e]_e = [e']_e : [c_1]_c \cap \ldots \cap [c_n]_c$, $\Gamma \vdash_{\cap CC} [e]_e : T_1 \cap \ldots \cap T_n$.
  - $\forall i \in 1..n \, . \, \mathit{isEmptyCast}\ [c_i]_c$: As all casts are empty casts, then for all casts $[c_i]_c$, by Lemma 6 and by rule T-EmptyC, $\vdash_{\cap IC} [c_i]_c : T_i$ and $\mathit{initialType}([c_i]_c) = T_i$. Therefore $[e]_e = [e']_e$. We now have two possibilities:
    * If $T$ is not an intersection type, then $T_1 = \ldots = T_n = T$ and by idempotence of $\cap$, we have that $\Gamma \vdash_{\cap CC} [e]_e : T_1 \cap \ldots \cap T_n$.
    * If $T$ is an intersection type, then $T = T_1 \cap \ldots \cap T_n$. Therefore $\Gamma \vdash_{\cap CC} [e]_e : T_1 \cap \ldots \cap T_n$.

(2) We proceed by induction on the length of the derivation tree of $\longrightarrow_{\cap CC}$.

Base cases:

- e $= (v_1 : cv_1 \cap \ldots \cap cv_n)\ v_2$ and $isValue((v_1 : cv_1 \cap \ldots \cap cv_n)\ v_2)$ and $\exists i \in 1..n \, . \, \mathit{isArrowCompatible}\ cv_i$. As $v_1 : cv_1 \cap \ldots \cap cv_n$ and $v_2$ are values, then $e$ doesn't contain identity casts. Therefore $[e]_e = e$.

- e $= v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2$ and $isValue\ v : cv_1 \cap \ldots \cap cv_n$ and $v : c_1' \cap \ldots \cap c_m' = mergeIC(v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2)$. There are 2 possibilities:

- If $T_1 \neq T_2$ and as $v : cv_1 \cap \ldots \cap cv_n$ doesn't contain identity casts, then $[e]_e = e$, therefore it is proved.
- If $T_1 = T_2$ and as $v : cv_1 \cap \ldots \cap cv_n$ doesn't contain identity casts, then $[e]_e = v : cv_1 \cap \ldots \cap cv_n$. By rule MergeIC$\cap$, $v : cv_1 \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2 \longrightarrow_{\cap CC} v : c'_1 \cap \ldots \cap c'_m$. By rule Evaluate$\cap$, $v : cv_1 : T_1 \Rightarrow^l T_2\ ^{m_1} \cap \ldots \cap cv_n : T_1 \Rightarrow^l T_2\ ^{m_n} \longrightarrow_{\cap CC} v : cv_1 \cap \ldots \cap cv_n$, with $cv_1 : T_1 \Rightarrow^l T_2\ ^{m_1} \longrightarrow_{\cap IC} cv_1$ and ... and $cv_n : T_1 \Rightarrow^l T_2\ ^{m_n} \longrightarrow_{\cap IC} cv_n$ by rule IdentityC. As $[e]_e$ is already a value, it is proved.

- e $= v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n$ and $isValue\ v : T_1 \Rightarrow^l T_2$ and $v : c'_1 \cap \ldots \cap c'_n = mergeCI(v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n)$. There are 2 possibilities:
  - $v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n$ doesn't contain identity casts, then $[e]_e = e$, therefore it is proved.
  - $v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n$ contain identity casts. By rule MergeCI$\cap$, $v : T_1 \Rightarrow^l T_2 : c_1 \cap \ldots \cap c_n \longrightarrow_{\cap CC} v : c'_1 \cap \ldots \cap c'_n$. By rule Evaluate$\cap$, $v : T_1 \Rightarrow^l T_2 : c'_1 \cap \ldots \cap c'_n \longrightarrow_{\cap CC} v : cv'_1 \cap \ldots \cap cv'_n$, with $c'_1 \longrightarrow_{\cap IC} cv'_1$ and ... and $c'_n \longrightarrow_{\cap IC} cv'_n$. For all casts $c_i$ that don't contain identity casts, then $[c_i]_c = c_i$, therefore for those casts, the property is proved. For all casts $c_i$ that contain identity casts, $mergeCI$ will generate casts $c'_i$ that will evaluate to $cv'_i$. By Lemma 6, casts $[c_i]_c$ will generate casts $c''_i$ that will evaluate to $cv'_i$, therefore it is proved.

- e $= v : cv_1 \cap \ldots \cap cv_n : c_1 \cap \ldots \cap c_m$ and $isValue\ v : cv_1 \cap \ldots \cap cv_n$ and $v : c'_1 \cap \ldots \cap c'_j = mergeII(v : cv_1 \cap \ldots \cap cv_n : c_1 \cap \ldots \cap c_m)$. There are 2 possibilities:
  - $v : cv_1 \cap \ldots \cap cv_n : c_1 \cap \ldots \cap c_m$ doesn't contain identity casts, then $[e]_e = e$, therefore it is proved.
  - $v : cv_1 \cap \ldots \cap cv_n : c_1 \cap \ldots \cap c_m$ contain identity casts. By rule MergeII$\cap$, $v : cv_1 \cap \ldots \cap cv_n : c_1 \cap \ldots \cap c_m \longrightarrow_{\cap CC} v : c'_1 \cap \ldots \cap c'_j$. By rule Evaluate$\cap$, $v : c'_1 \cap \ldots \cap c'_j \longrightarrow_{\cap CC} v' : cv'_1 \cap \ldots \cap cv'_j$, with $c'_1 \longrightarrow_{\cap IC} cv'_1$ and ... and $c'_j \longrightarrow_{\cap IC} cv'_j$. For all casts $cv_i$ and $c_i$ that will be joined into $c'_i$ by function mergeII, and that don't contain identity casts, then $[c'_i]_c = c'_i$, therefore for those casts, the property is proved. For all casts $cv_i$ and $c_i$ that will be joined into $c'_i$ by function mergeII, and that contain identity casts, $c'_i \longrightarrow_{\cap IC} cv'_i$ and by Lemma 6, $[c'_i]_c \longrightarrow_{\cap IC} cv'_i$, therefore it is proved.

- e $= v : c_1 \cap \ldots \cap c_n$ and $\neg(\forall i \in 1..n\ .\ isCastValue\ c_i)$. By rule Evaluate$\cap$, $v : c_1 \cap \ldots \cap c_n \longrightarrow_{\cap CC} v : cv_1 \cap \ldots \cap cv_n$, with $c_1 \longrightarrow_{\cap IC} cv_1$ and ... and $c_n \longrightarrow_{\cap IC} cv_n$. With $[e]_e = v : [c_1]_c \cap \ldots \cap [c_n]_c$, by Lemma 6, $[c_1]_c \longrightarrow_{\cap IC} cv_1$ and ... and $[c_n]_c \longrightarrow_{\cap IC} cv_n$. Therefore, by rule Evaluate$\cap$, $v : [c_1]_c \cap \ldots \cap [c_n]_c \longrightarrow_{\cap CC} v : cv_1 \cap \ldots \cap cv_n$.

- e $= v : blame\ I_1\ F_1\ l_1\ ^{m_1} \cap \ldots \cap blame\ I_n\ F_n\ l_n\ ^{m_n}$. As $[e]_e = e$, then it is proved.

- e $= v : \varnothing\ T_1\ ^{m_1} \cap \ldots \cap \varnothing\ T_n\ ^{m_n}$. As $[e]_e = e$, then it is proved.

Induction step:

- e =

$\square$