Spine-local Type Inference: Proof Appendix

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1  Type Inference Rules

1.1  Syntax

Types
\[ S, T, U, V ::= X, Y, Z \mid S \to T \mid \forall X. T \]

Contexts
\[ \Gamma ::= \cdot \mid \Gamma, X \mid \Gamma, x : T \]

Terms (Internal)
\[ e, p ::= x \mid \lambda x : T . e \mid \Lambda X . e \mid e e' \mid e[T] \]

Terms (External)
\[ t ::= x \mid \lambda x : T . t \mid \lambda x . t \mid \Lambda X . t \mid t t' \mid t[T] \]

Prototypes
\[ P ::= ? \mid T \mid ? \to P \]

Decorated Types
\[ W ::= T \mid S \to W \mid \forall X = X . W \mid \forall X = S . W \mid (X, ? \to P) \]

1.2  Terminology

In both the internal and external languages, we say that the applicand of a term or type application is the term in the function position. A head is either a variable or λ-abstraction (bare or annotated), and an application spine (or just spine) is a view of an application as consisting of some head (called the spine head) followed by a sequence of (term and type) arguments. The maximal application of a sub-expression is the spine in which it occurs as an applicand, or just the sub-expression itself if it does not. For example, spine \( x[S] y z \) is the maximal application of itself and its applicand sub-expressions \( x, x[S], \) and \( x[S] y, \) with \( x \) as head of the spine. Predicate \( \text{App}(t) \) indicates term \( t \) is some term or type application (in either language) and we define it formally as \( (\exists t_1, t_2. \ t = t_1 t_2) \lor (\exists t', S. \ t = t'[S]) \). Finally, for any application \( e_1 e_2 \) we shall call a term applicand* any applicand occurring in the spine of \( e_1 \).

Turning to definitions for types and contexts, function \( DTV(\Gamma) \) calculates the set of declared type variables of context \( \Gamma \) and is defined recursively by the following set of equations:

\[
\begin{align*}
DTV(\cdot) &= \emptyset \\
DTV(\Gamma, X) &= DTV(\Gamma) \cup \{X\} \\
DTV(\Gamma, x : T) &= DTV(\Gamma)
\end{align*}
\]

Predicate \( WF(\Gamma, T) \) indicates that type \( T \) is well-formed under \( \Gamma \) – that is, all free type variables of \( T \) occur as declared type variables in \( \Gamma \) (formally \( \text{FV}(T) \subseteq DTV(\Gamma) \)).
1.3 Meta-language Definitions

\[ T_{\text{mApp}}(t) = (\exists t_1, t_2. \ t = t_1 t_2) \]
\[ T_{\text{pApp}}(t) = (\exists t', S. \ t = t'[S]) \]
\[ \text{App}(t) = T_{\text{mApp}}(t) \lor T_{\text{pApp}}(t) \]

\[ WF(\Gamma, T) = (FV(T) - \text{DTV}(\Gamma) = \emptyset) \]
\[ WF(\Gamma, ?) = \text{True} \]
\[ WF(\Gamma, ? \rightarrow P) = WF(\Gamma, P) \]

\[ \text{DTV}(\cdot) = \emptyset \]
\[ \text{DTV}(\Gamma, X) = \text{DTV}(\Gamma) \cup \{X\} \]
\[ \text{DTV}(\Gamma, x : T) = \text{DTV}(\Gamma) \]

\[ \text{MV}(\Gamma, p) = \emptyset \text{ when } \neg \text{App}(p) \]
\[ \text{MV}(\Gamma, p[X]) = \text{MV}(\Gamma, p) \cup \{X\} \text{ when } X \notin \text{DTV}(\Gamma) \]
\[ \text{MV}(\Gamma, p[S]) = \text{MV}(\Gamma, p) \text{ when } WF(\Gamma, S) \]
\[ \text{MV}(\Gamma, p \ e) = \text{MV}(\Gamma, p) \]

\[ \lfloor \lambda x : T. e \rfloor = \{ \lambda x : T. t \mid t \in \lfloor e \rfloor \} \cup \{ \lambda x. t \mid t \in \lfloor e \rfloor \} \]
\[ \lfloor \Lambda X. e \rfloor = \{ \Lambda X. t \mid t \in \lfloor e \rfloor \} \]
\[ \lfloor e e' \rfloor = \{ t t' \mid t \in \lfloor e \rfloor \land t' \in \lfloor e' \rfloor \} \]
\[ \lfloor e[S] \rfloor = \{ t[S] \mid t \in \lfloor e \rfloor \} \]
\[ \lfloor e[S] \rfloor_a = \{ t \mid t \in \lfloor e \rfloor \}_a \cup \{ t[S] \mid t \in \lfloor e \rfloor \} \]
\[ \lfloor e \rfloor_a = \lfloor e \rfloor \text{ otherwise} \]

\[ \lfloor S \rightarrow W \rfloor = S \rightarrow \lfloor W \rfloor \]
\[ \lfloor \forall X = R. W \rfloor = \forall X. \lfloor W \rfloor \]
\[ \lfloor (X, ? \rightarrow P) \rfloor = X \]

\[ \text{arr}_{\text{P}}(?) = \text{arr}_{\text{P}}(T) = 0 \]
\[ \text{arr}_{\text{P}}(? \rightarrow P) = 1 + \text{arr}_{\text{P}}(P) \]
\[ \text{arr}_{\text{W}}((X, ? \rightarrow P)) = \text{arr}_{\text{W}}(T) = 0 \]
\[ \text{arr}_{\text{W}}(\forall X = R. W) = \text{arr}_{\text{W}}(W) \]
\[ \text{arr}_{\text{W}}(S \rightarrow W) = 1 + \text{arr}_{\text{W}}(W) \]
1.4 Bidirectional Rules

\[
\begin{array}{ll}
\Gamma \vdash t : T \rightarrow e & \Rightarrow \quad \Gamma \vdash x : \Gamma(x) \rightarrow x \quad \text{Var} \\
\Gamma, x : T \vdash t : S \rightarrow e & \Rightarrow \quad \Gamma \vdash \lambda x : T. t : S \rightarrow \lambda x : T. e \quad \text{Abs} \\
\Gamma, X \vdash t : T \rightarrow e & \Rightarrow \quad \Gamma \vdash \Lambda X. t : \forall X.T \rightarrow \Lambda X. e \quad \text{TAbs} \\
\Gamma \vdash t[S] : [S/X]T \rightarrow e[S] & \Rightarrow \quad \text{TApp}
\end{array}
\]

\[
\begin{array}{ll}
\Gamma ; ? \vdash t t' : T \rightarrow (e, \sigma_{id}) & \Rightarrow \quad \text{AppSyn} \\
\Gamma \vdash t t' : T \rightarrow e & \Rightarrow \quad \text{AppChk}
\end{array}
\]

Figure 1: Bidirectional inference rules with elaboration
1.5 Specificational Rules

(a) Shim (specification)

\[
\begin{align*}
\Gamma \vdash^{P} t \ T' : T & \leadsto (p, \sigma) \\
MV(\Gamma, T) &= \text{dom}(\sigma) \\
T_? := T | ?
\end{align*}
\]

\[
\begin{align*}
\Gamma; T_? \vdash t \ T' : T & \leadsto (p, \sigma) \\
\end{align*}
\]

(b) \[
\Gamma \vdash^{P} t : T \leadsto (p, \sigma)
\]

\[
\frac{\neg \text{App}(t) \quad \Gamma \vdash_0 t : T \leadsto e}{\Gamma \vdash^{P} t : T \leadsto (e, \sigma_{id})} \quad \text{PHead}
\]

\[
\frac{\Gamma \vdash^{P} t : T \leadsto (p, \sigma) \quad \Gamma \vdash (p: T, \sigma) \cdot t' : T' \leadsto (p', \sigma')}{\Gamma \vdash^{P} t \ t' : T' \leadsto (p', \sigma')} \quad \text{PApp}
\]

\[
\frac{\sigma'' \in \{\sigma, [S/X] \circ \sigma\} \quad WF(\Gamma, S) \quad \Gamma \vdash (p: \forall X.T, \sigma'') \cdot t' : T' \leadsto (p', \sigma')}{\Gamma \vdash (p: \forall X.T, \sigma) \cdot t' : T' \leadsto (p', \sigma')} \quad \text{PForall}
\]

\[
\frac{\text{MV}(\Gamma, \sigma, S) = \emptyset \quad \Gamma \vdash_0 t' : \sigma \ S \leadsto e'}{\Gamma \vdash (p: S \rightarrow T, \sigma) \cdot t' : [U/Y] \ T \leadsto ([U/Y] p) e', \sigma)} \quad \text{PChk}
\]

\[
\frac{\text{MV}(\Gamma, \sigma, S) = \emptyset \quad \Gamma \vdash_0 t' : \sigma \ S \leadsto e'}{\Gamma \vdash (p: S \rightarrow T, \sigma) \cdot t' : [U/Y] \ T \leadsto ([U/Y] p) e', \sigma)} \quad \text{PSyn}
\]

Figure 2: Specification for contextual type-argument inference
1.6 Algorithmic Rules

(a) Shim (algorithm)

\[ \Gamma; T \vdash t : T \rightarrow (p, \sigma) \]

(b) Shim (algorithm)

\[ \Gamma; P \vdash t : W \rightarrow (p, \sigma) \]

(c) Shim (algorithm)

\[ \sigma'' = \text{if } R = X \text{ then } \sigma \text{ else } [R/X] \sigma \]
2 Soundness of $\vdash_\delta$ wrt $\vdash$

Our soundness statement for the external language is that every well-typed term of the external language elaborates to a well-typed term of the internal language, and it is proven using mutual induction on the following three theorems.

1. If $\Gamma \vdash_\delta t : T \rightsquigarrow e$ then $\Gamma \vdash e : T$
2. If $\Gamma \vdash^P t : T \rightsquigarrow (p, \sigma)$ then $\Gamma, MV(\Gamma, \sigma p) \vdash \sigma p : \sigma \tau$
3. If $\Gamma \vdash (p : T, \sigma) \cdot t' : T' \rightsquigarrow (p', \sigma')$ and $\Gamma, MV(\Gamma, \sigma p) \vdash \sigma p : \sigma \tau$ where
   - $\text{dom}(\sigma) \subseteq MV(\Gamma, p)$
   - For all $X \in \text{dom}(\sigma), WF(\Gamma, \sigma(X))$
   - $\text{dom}(\sigma) \cap BTV(\text{cod}(\sigma)) = \emptyset$

then $\Gamma, MV(\Gamma, \sigma' p') \vdash \sigma' p' : \sigma' \tau T'$

2.1 Bidirectional Rules

Theorem 1. (Soundness of $\vdash_\delta$): If $\Gamma \vdash_\delta t : T \rightsquigarrow e$ then $\Gamma \vdash e : T$

Proof. By mutual induction of the assumed derivation.

Case $\text{Var}$: Directly from assumption

$$\Gamma \vdash x : \Gamma(x) \quad \text{Var}$$

Case $\text{AAbs}$: Our assumed derivation is

$$\Gamma, x : T \vdash_\delta t : S \rightsquigarrow e$$

$$\Gamma \vdash_\delta \lambda x : T. t : T \rightarrow S \rightsquigarrow \lambda x : T. e \quad \text{AAbs}$$

Invoking the IH on the premise we get $\Gamma, x : T \vdash e : S$ so we can conclude with

$$\Gamma, x : T \vdash e : S \quad \text{FAbs}$$

Case $\text{Abs}$: Similar to $\text{AAbs}$, invoking the IH on the premise (specialized to $\vdash^P$) and using $\text{FAbs}$.

Case $\text{TAbs}$: Similar to $\text{AAbs}$, invoking the IH on the premise and using $\text{FTAbs}$

Case $\text{TApp}$: Similar to $\text{AAbs}$ and $\text{TAbs}$, invoking the IH on the premise (specialized to $\vdash^P$) and using $\text{FTApp}$.

Case $\text{AppSyn}$: Our assumed derivation (after in-lining judgment $\vdash^P$) is

$$\Gamma \vdash^P t t : T \rightsquigarrow (e, \sigma_{id}) \quad MV(\Gamma, e) = MV(\Gamma, T) = \emptyset \quad \text{AppSyn}$$

By mutual induction on Theorem 2 (soundness of $\vdash^P$) on the first premise, we have

$$\Gamma, MV(\Gamma, e) \vdash \sigma_{id} e : \sigma_{id} T$$

which after a little re-writing gives us

$$\Gamma \vdash e : T$$

which is what we need.
Caase AppChk: Our assumed derivation is

\[
\Gamma \vdash P \quad \text{MV}(\Gamma, p) = \text{MV}(\Gamma, T) = \text{dom}(\sigma)
\]

\[
\Gamma \vdash \gamma \quad t \, t' : T \rightsquigarrow \sigma
\]

By mutual induction on Theorem 2\(^2\) (soundness of \(\vdash\)) on the first premise, we have

\[
\Gamma, \text{MV}(\Gamma, \sigma p) \vdash \sigma p : \sigma T
\]

Since we know (from the second premise of our assumed derivation) that \(\text{MV}(\Gamma, p) = \text{dom}(\sigma)\), we know that \(\text{MV}(\Gamma, \sigma p) = \emptyset\), so we can rewrite to

\[
\Gamma \vdash \sigma p : \sigma T
\]

which is what we need.

\[\square\]

2.2 Partial Synthesis Rules

Theorem 2. (Soundness of \(\vdash\)):

If \(\Gamma \vdash P \, t : T \rightsquigarrow (p, \sigma)\) then \(\Gamma, \text{MV}(\Gamma, \sigma p) \vdash \sigma p : \sigma T\)

Proof. By mutual induction on the assumed derivation.

Case PHead: Our assumed derivation is

\[
\neg \text{App}(t) \quad \Gamma \vdash \gamma \quad t : T \rightsquigarrow e
\]

\[
\Gamma \vdash \gamma \quad t : T \rightsquigarrow (e, \sigma_{id}) \quad \text{PHead}
\]

By mutual induction on the soundness of \(\vdash\) on the second premise we get

\[
\Gamma \vdash e : T
\]

Since \(e\) is well-typed under \(\Gamma\) using the internal typing rules it has no metavariables. Therefore, \(\text{MV}(\Gamma, e) = \emptyset\), and we conclude

\[
\Gamma, \emptyset \vdash \sigma_{id} e : \sigma_{id} T
\]

Case PTApr: Our assumed derivation is

\[
\Gamma \vdash \gamma \quad t : \forall X. T \rightsquigarrow (p, \sigma)
\]

\[
\Gamma \vdash \gamma \quad t[S] : [S/X]T \rightsquigarrow (p[S], \sigma) \quad \text{ITApp}
\]

By the IH on our premise we get

\[
\Gamma, \text{MV}(\Gamma, \sigma p) \vdash \sigma p : \sigma \forall X. T
\]

Implicit here is that \(WF(\Gamma, S)\), so \(\text{MV}(\Gamma, p[S]) = \text{MV}(\Gamma, p)\), and bound \(X\) is fresh w.r.t. \(\Gamma, p, \) and \(\sigma\), so \(\sigma \forall X. T = \forall X. \sigma T\). We conclude

\[
\Gamma, \text{MV}(\Gamma, \sigma p[S]) \vdash \sigma p : \forall X. \sigma T
\]

\[
\Gamma, \text{MV}(\Gamma, \sigma p[S]) \vdash \sigma p[S] : [S/X] \sigma T \quad \text{FTApp}
\]

Case PApp: Our assumed derivation is

\[
\Gamma \vdash \gamma \quad t : T \rightsquigarrow (p, \sigma)
\]

\[
\Gamma \vdash \gamma \quad (p : T, \sigma) \cdot t' : T' \rightsquigarrow (p', \sigma') \quad \text{IApp}
\]

By the IH on the premise we have

\[
\Gamma, \text{MV}(\Gamma, \sigma p) \vdash \sigma p : \sigma T
\]

With this and with the second premise of our assumed derivation, we need to invoke mutual induction on Theorem 3\(^3\) (soundness of \(\vdash\)) to get
\( \Gamma, MV(\Gamma, \sigma') \vdash \sigma' \ p' : \sigma' \ T' \).

To do so, we must meet the pre-requisite of Theorem 3, \( dom(\sigma) \subseteq MV(\Gamma, p) \) for all \( X, WF(\Gamma, \sigma(X)) \), and that \( dom(\sigma) \cap BTV(cod(\sigma)) = \emptyset \). The first two of these we have from Lemma 1 and the last of these we have from Lemma 2.

### 2.3 Partial Application Rules

**Theorem 3.** (Soundness of \( \vdash \) wrt \( \delta \)): If \( \Gamma \vdash_{\delta} (p:T, \sigma) \cdot t' : T' \rightsquigarrow (p', \sigma') \) and \( \Gamma, MV(\Gamma, \sigma) p) \vdash \sigma p : \sigma T \) where

- \( dom(\sigma) \subseteq MV(\Gamma, p) \)
  
  Our solution set \( \sigma \) really solves meta-variables.

- For all \( X \in dom(\sigma), WF(\Gamma, \sigma(X)) \)
  
  Our solution set \( \sigma \) really solves meta-variables.

- \( dom(\sigma) \cap BTV(cod(\sigma)) = \emptyset \)
  
  No meta-variables are ever generated by solutions in \( \sigma \)

then \( \Gamma, MV(\Gamma, \sigma') p' \vdash \sigma' p' : \sigma' T' \)

**Proof.** By mutual induction on the assumed derivation of \( \vdash \).

**Case PForall:** Our assumed derivations are

\[
\sigma'' \in \{ \sigma, [S/X] \circ \sigma \}, WF(\Gamma, S) \quad \Gamma \vdash_{\delta} (p[X]:T, \sigma'') \cdot t' : T' \rightsquigarrow (p', \sigma') \quad PForall \quad \text{and} \quad \Gamma, MV(\Gamma, \sigma) p) \vdash \sigma p : \sigma \forall X.T
\]

We perform case analysis on \( \sigma'' \): either \( \sigma'' = \sigma \) or \( \sigma'' = \sigma \circ [S/X] \). If it is the former, then since \( X \) is fresh wrt \( \sigma \) we have \( MV(\Gamma, \sigma'' p[X]) = MV(\Gamma, \sigma p) \cup \{ X \} \) and \( \sigma'' p[X] = \sigma p[X] \). We have by weakening

\[
\Gamma, MV(\Gamma, \sigma) p) \vdash \sigma p : \sigma \forall X.T \quad \text{Weaken}
\]

If \( \sigma'' = [S/X] \circ \sigma \) then we have \( MV(\Gamma, \sigma'' p[X]) = MV(\Gamma, \sigma p[S]) = MV(\Gamma, \sigma p) \) and we need only rewrite our second assumed derivation to \( \Gamma, MV(\Gamma, \sigma'' p[X]) \vdash \sigma'' p : \sigma \forall X.T \)

In both cases, we can derive

\[
\Gamma, MV(\Gamma, \sigma'' p) \vdash \sigma'' p : \sigma \forall X.T \quad \text{TAppF}
\]

We are now ready to invoke the IH with this and with the second premise of our assumed derivation of \( \vdash \) to derive

\[
\Gamma, MV(\Gamma, \sigma') p' \vdash \sigma' p' : \sigma' T'
\]

which is what we need to conclude. (Note that our third condition is satisfied for \( \sigma'' \) since bound variable \( X \) occurs before applying substitution \( \sigma \).)

**Case PChk:** Our assumed derivations are

\[
MV(\Gamma, \sigma S) = \emptyset \quad \Gamma \vdash_{\delta} t' : \sigma S \rightsquigarrow e' \quad PChk \quad \text{and} \quad \Gamma, MV(\Gamma, \sigma) p) \vdash \sigma p : \sigma S \rightarrow T
\]

By mutual induction on Theorem 1 (soundness of \( \vdash_{\delta} \) wrt \( \vdash \)) and by weakening we have

\[
\Gamma \vdash_{\delta} e' : \sigma S \quad \text{Sound} \quad \Gamma, MV(\Gamma, \sigma) p) \vdash e' : \sigma S \quad \text{Weaken}
\]

With this and our second assumption, the derivation of \( \vdash \), we can conclude

\[
\Gamma, MV(\Gamma, \sigma) p) \vdash \sigma p : \sigma S \rightarrow T \quad \Gamma, MV(\Gamma, \sigma) p) \vdash e' : \sigma S \quad \text{App}
\]

noting that since \( e' \) is well-typed under \( \Gamma, \sigma e' = e' \).
Proof. By a similar argument to Theorem 2 and Theorem 3, we can strengthen the two theorems above to yield:

\[ MV(\Gamma, \sigma S) = \emptyset \neq \emptyset \quad \Gamma \vdash t' : [U/Y] \sigma S \rightsquigarrow e' \quad P_{Syn} \]

\[ \Gamma \vdash (p:S \rightarrow T, \sigma) \cdot t' : [U/Y] T \rightsquigarrow (\emptyset) T \quad (p e'), \sigma) \quad \text{and} \quad \Gamma, MV(\Gamma, \sigma p) \vdash \sigma p : \sigma S \rightarrow T \]

By mutual induction on Theorem 1 (soundness of \( \vdash \)) and weakening on the second premise of our assumed derivation of \( \vdash \) we have

\[ \Gamma \vdash t' : [U/Y] \sigma S \rightsquigarrow e' \quad Sound \vdash \]

\[ \Gamma, MV(\Gamma, [U/Y] \sigma p) \vdash e' : [U/Y] \sigma S \quad Weaken \]

By induction on the assumed derivations where the first invokes the second. Note that only rule \( P_{Forall} \) adds any meta-variable solutions and that these are generated from a type that does not have access to solutions in the input substitution \( \sigma \).

2.4 Lemma: Well-formed and well-scoped solutions

Lemma 1.

- If \( \Gamma \vdash t : T \rightsquigarrow (p, \sigma) \) then \( \text{dom}(\sigma) \subseteq MV(\Gamma, p) \) and for all \( X \in \text{dom}(\sigma), WF(\Gamma, \sigma(X)) \).
- If \( \text{dom}(\sigma) \subseteq MV(\Gamma, p) \) and for all \( X \in \text{dom}(\sigma), WF(\Gamma, \sigma(X)) \), and if \( \Gamma \vdash (p : T, \sigma) \cdot t' : T' \rightsquigarrow (p', \sigma') \), then \( \text{dom}(\sigma') \subseteq MV(\Gamma, p') \) and for all \( X \in \text{dom}(\sigma'), WF(\Gamma, \sigma'(X)) \)

Proof. Straightforward induction on the assumed derivation where the first invokes the second.

2.5 Lemma: \( \sigma \) introduces no meta-variables

Lemma 2.

- If \( \Gamma \vdash t : T \rightsquigarrow (p, \sigma) \) then \( \text{dom}(\sigma) \cap BTV(\text{cod}(\sigma)) = \emptyset \)
- If \( \text{dom}(\sigma) \subseteq MV(\Gamma, p) \) and for all \( X \in \text{dom}(\sigma), WF(\Gamma, \sigma(X)) \), then \( \text{dom}(\sigma') \cap BTV(\text{cod}(\sigma')) = \emptyset \)

Proof. By induction on the assumed derivations where the first invokes the second. Note that only rule \( P_{Forall} \) adds any meta-variable solutions and that these are generated from a type that does not have access to solutions in the input substitution \( \sigma \).

2.6 Lemma: Sound use of \( \sigma \) on \( \vdash \)

Lemma 3. If \( \Gamma, MV(\Gamma, p) \vdash p : T \) and \( \text{dom}(\sigma) \subseteq MV(\Gamma, p) \) and for all \( X \in \text{dom}(\sigma), WF(\Gamma, \sigma(X)) \), then \( \Gamma, (\overline{X} - \text{dom}(\sigma)) \vdash p : \sigma S \rightarrow T \)

Proof. By induction on the assumed derivation.

2.7 Lemma: Well-formed Partial Types

Lemma 4.

- If \( \Gamma \vdash t : T \rightsquigarrow (p, \sigma) \) then \( WF(\Gamma', T) \) where \( \Gamma' = \Gamma, MV(\Gamma, p) \).
- If \( \Gamma \vdash (p : T, \sigma) \cdot t' : T' \rightsquigarrow (p', \sigma') \) and \( WF(\Gamma', T) \) (where \( \Gamma' = \Gamma, MV(\Gamma, p) \)), then \( WF(\Gamma', T') \)

Proof. By a similar argument to Theorem 2 and Theorem 3 we can strengthen the two theorems above to yield:
Proof. By straightforward induction on the assumed derivation. The rules of the two systems are identical except for Theorem 4.

If \( p : T, \sigma \cdot t' : T' \leadsto (p', \sigma') \) and \( MV(\Gamma, p) \vdash p : T \) then \( \Gamma, MV(\Gamma, p') \vdash p' : T' \)

and from there, reason that any term well-typed by the internal typing rules was typed with a well-formed type. \( \square \)

3 Soundness of \( \models_\delta \) wrt \( \vdash_\delta \)

Soundness of the algorithmic rules means that any external term typeable with the algorithmic rules is also typeable with the specificational rules, and is shown by mutual induction on the following three theorems:

1. If \( \Gamma \models_\delta t : T \leadsto e \) then \( \Gamma \vdash_\delta t : T \leadsto e \)
2. If \( \Gamma; P \models_\delta t : W \leadsto (p, \sigma) \) then \( \Gamma \vdash_\delta t : [W] \leadsto (p, \sigma) \)
3. If \( \Gamma \vdash_\delta (p : W, \sigma) \cdot t' : W' \leadsto (p', \sigma') \) and \( MV(\Gamma, p) \models_\delta [W] := ? \Rightarrow P \Rightarrow (\sigma, W) \) with \( WF(\Gamma, ? \Rightarrow P) \)

Then \( \Gamma \vdash_\delta (p : [W], \sigma) \cdot t' : [W'] \leadsto (p', \sigma') \)

Where \( \models_\delta \) indicates the bidirectional rules using the shim judgment defined in Figure 3a.

3.1 Bidirectional Rules

Theorem 4. If \( \Gamma \models_\delta t : T \leadsto e \) then \( \Gamma \vdash_\delta t : T \leadsto e \)

Proof. By straightforward induction on the assumed derivation. The rules of the two systems are identical except for \( AppSyn \) and \( AppChk \), so only these are shown.

Case \( AppSyn \): Our assumed derivation is

\[
\frac{\Gamma; ? \models_\delta t \cdot t' : T \leadsto (e, \sigma_{id}) \quad MV(\Gamma, e) = \emptyset}{\Gamma \models_\delta t \cdot t' : T \leadsto e} \quad \text{AppSyn}
\]

By mutual induction of sound \( \models_\delta \) on the first premise, we have

\( \Gamma \vdash_\delta t \cdot t' : T \leadsto (e', \sigma_{id}) \) (since \( [T] = T \)).

We now need to satisfy the specificational condition that \( MV(\Gamma, T) = dom(\sigma_{id}) = \emptyset \). We have via Lemma 4 (well-formedness of synthesized partial types) that \( WF(\Gamma, T) \) which guarantees this. We can now conclude

\[
\frac{\Gamma \vdash_\delta t \cdot t' : T \leadsto (e, \sigma_{id}) \quad MV(\Gamma, T) = MV(\Gamma, e) = \emptyset}{\Gamma \models_\delta t \cdot t' : T \leadsto e} \quad \text{AppSyn}
\]

Case \( AppChk \): Our assumed derivation is

\[
\frac{\Gamma; T \models_\delta t \cdot t' : T \leadsto (p, \sigma) \quad MV(\Gamma, p) = dom(\sigma)}{\Gamma \models_\delta t \cdot t' : \sigma \cdot T \leadsto \sigma p} \quad \text{AppChk}
\]

By mutual induction on Theorem 5 (Soundness of prototype synthesis) on the first premise, we have

\( \Gamma \vdash_\delta t \cdot t' : T \leadsto (p, \sigma) \)

The last condition we need to meet for the specificational version of \( AppChk \) is that \( MV(\Gamma, T) = dom(\sigma) \). We first note that by Lemma 4 that \( WF(\Gamma', T) \) (where \( \Gamma' = \Gamma, MV(\Gamma, p) \)). Next, we invoke Lemma 6 (prototype synthesis preserves matching) to get \( MV(\Gamma, p) \models_\delta T := \sigma \Rightarrow (\sigma, T) \)

By inversion, the only rule that could form this match is \( MType \), which after a little rewriting in terms of meta-variables and \( \sigma \) gives us:

\[
\frac{dom(\sigma) = FV(T) \cap MV(\Gamma, p)}{MV(\Gamma, p) \models_\delta T := \sigma \Rightarrow (\sigma, T) \quad MType}
\]
and this premise is equivalent to saying \( \text{dom}(\sigma) = \text{MV}(\Gamma, T) \) (since by Lemma 1 we have that \( \text{WF}(\Gamma', T) \) where \( \Gamma' = \Gamma, \text{MV}(\Gamma, p) \)). We can conclude

\[
\frac{\Gamma \vdash P \quad t' : T \rightsquigarrow (p, \sigma) \quad \text{MV}(\Gamma, p) = \text{MV}(\Gamma, T) = \text{dom}(\sigma)}{\Gamma \vdash_{\text{AppChk}} t' : \sigma T \rightsquigarrow \sigma p}
\]

\[\square\]

### 3.2 Prototype Rules

**Theorem 5.** If \( \Gamma; P \models t : W \rightsquigarrow (p, \sigma) \) then \( \Gamma \vdash P \models t : [W] \rightsquigarrow (p, \sigma) \)

**Proof.** By induction on the assumed derivation.

**Case ?Head:** Our assumed derivation is

\[
\frac{\neg \text{App}(t) \quad \Gamma \models t : T \rightsquigarrow e \quad \varnothing \models ? T := \Rightarrow P \Rightarrow (\sigma_{id}, W)}{\Gamma; ? \Rightarrow P \models ? t : W \rightsquigarrow (e, \sigma_{id})}
\]

By mutual induction on the soundness of \( \models ? \) we have

\[
\frac{\Gamma \vdash t : T \rightsquigarrow e}{\Gamma \vdash_{\text{Theorem 1}} t : T \rightsquigarrow e}
\]

We now to construct

\[
\frac{\neg \text{App}(t) \quad \Gamma \models t : T \rightsquigarrow e}{\Gamma \vdash P \models t : (e, \sigma_{id})}
\]

**Case ?TApp:** Our assumed derivation is

\[
\frac{\Gamma; ? \Rightarrow P \models ? t : \forall X = R.W \rightsquigarrow (p, \sigma) \quad R \in \{X, S\}}{\Gamma; ? \Rightarrow P \models [S/X]W \rightsquigarrow (p[S], \sigma)}
\]

By the IH on the first premise we have

\[
\frac{\Gamma \vdash P \models \forall X. [W] \rightsquigarrow (p, \sigma)}{\Gamma \vdash P \models \forall X. [W] \rightsquigarrow (p, \sigma)}
\]

We can conclude with

\[
\frac{\Gamma \vdash P \models \forall X. [W] \rightsquigarrow (p, \sigma)}{\Gamma \vdash P \models \forall X. [W] \rightsquigarrow (p, \sigma)}
\]

where it’s clear that \([S/X] \cdot [W] = [[S/X] \cdot W]\)

**Case ?App** Our assumed derivation is

\[
\frac{\Gamma; ? \Rightarrow P \models ? t : W \rightsquigarrow (p, \sigma) \quad \Gamma \vdash \cdot (p:W, \sigma) \cdot t' : W' \rightsquigarrow (p', \sigma)' \quad \text{App}}{\Gamma; P \models ? t' : W' \rightsquigarrow (p', \sigma)'}
\]

By the IH on the first premise we have

\[
\frac{\Gamma \vdash P \models t : [W] \rightsquigarrow (p, \sigma)}{\Gamma \vdash P \models t : [W] \rightsquigarrow (p, \sigma)}
\]

by Lemma 3 we can derive

\[
\frac{\text{MV}(\Gamma, p) \models ? [W] := ? \Rightarrow P \Rightarrow (\sigma, W)}{\Gamma \vdash \cdot (p:[W], \sigma) \cdot t' : [W'] \rightsquigarrow (p', \sigma)'}
\]

This match lets us invoke mutual induction on Theorem 6 (soundness of \( \models \cdot \)) on the second premise, and we have

\[
\frac{\Gamma \vdash \cdot (p:[W], \sigma) \cdot t' : [W'] \rightsquigarrow (p', \sigma)'}{\Gamma \vdash \cdot (p:[W], \sigma) \cdot t' : [W'] \rightsquigarrow (p', \sigma)'}
\]

We can conclude with

\[
\frac{\Gamma \vdash P \models t : [W] \rightsquigarrow (p, \sigma) \quad \Gamma \vdash \cdot (p:[W], \sigma) \cdot t' : [W'] \rightsquigarrow (p', \sigma)'}{\Gamma \vdash P \models t' : [W'] \rightsquigarrow (p', \sigma)'}
\]

\[\square\]
3.3 Prototype Application Rules

Theorem 6. If $\Gamma \vdash (p:W,\sigma) \cdot t': W' \leadsto (p',\sigma')$ and $MV(\Gamma, p) \vdash W := ? \Rightarrow (\sigma, W)$ with $WF(\Gamma, ? \Rightarrow P)$ then $\Gamma \vdash (p:[W],\sigma) \cdot t': [W'] \leadsto (p',\sigma')$

Proof. By induction on the assumed derivation of $\vdash$.

Case $\text{Forall}$: Our assumed derivation for $\vdash$ is

$\sigma'' = \text{if } R = X \text{ then } \sigma \text{ else } [R/X] \circ \sigma \text{ } \Gamma \vdash (p[X]:W,\sigma'') \cdot t': W' \leadsto (p',\sigma')$ $\text{?Forall}$

and our assumed match is $MV(\Gamma, p) \vdash \forall X. [W] := ? \Rightarrow (\sigma, \forall X = R, W)$

The only rule that could result in this conclusion is $\text{MVForall}$, whose premise is $MV(\Gamma, p), X \vdash [W] := ? \Rightarrow (R/X) \circ \sigma, W)$

We appeal to Lemma $\square$ on the well-formedness of solutions in $[R/X] \circ \sigma$ to get $R = X$ or $WF(\Gamma, R)$. This makes $R$ a legal guess for our specification system. Now we invoke the IH (using the match directly above and the second premise of our assumed derivation of $\vdash$) to get $\Gamma \vdash (p[X]:[W], [R/X] \circ \sigma) \cdot t': [W'] \leadsto (p',\sigma')$

allowing us to conclude $\Gamma \vdash (p: \forall X. [W], \sigma) \cdot t': [W'] \leadsto (p',\sigma')$

Case $\text{Chk}$: Our assumed derivation is

$MV(\Gamma, \sigma, S) = \emptyset \text{ } \Gamma \vdash t': \sigma, S \leadsto e$ $\text{Chk}$

and our assumed match is $MV(\Gamma, p) \vdash S \Rightarrow [W] := ? \Rightarrow (\sigma, S \Rightarrow W)$

By mutual induction on Theorem 3 (soundness of $\vdash \emptyset$) on the second premise we have $\Gamma \vdash t': \sigma, S \leadsto e$. We can conclude

$MV(\Gamma, \sigma, S) = \emptyset \text{ } \Gamma \vdash (p:S \Rightarrow [W]) \cdot t': [W] \leadsto (p\ e',\sigma)$ $\text{PChk}$

Case $\text{Syn}$: Our assumed derivation is

$MV(\Gamma, \sigma, S) = \emptyset \text{ } \Gamma \vdash t: [U/Y] \sigma, S \leadsto e$ $\text{Syn}$

and our assumed match is $MV(\Gamma, p) \vdash S \Rightarrow [W] := ? \Rightarrow (\sigma, S \Rightarrow W)$

By mutual induction on the soundness of $\vdash \emptyset$ we have $\Gamma \vdash t: [U/Y] \sigma, S \leadsto e$

which allows us to conclude

$MV(\Gamma, \sigma, S) = \emptyset \text{ } \Gamma \vdash (p:S \Rightarrow [W]) \cdot t': [U/Y] \sigma, S \leadsto e$ $\text{PSyn}$

3.4 Lemma: Sound decoration erasure

Lemma 5. If $\overline{X} \vdash T := P \Rightarrow (\sigma, W)$ then $[W] = T$
3.5 Lemma: Sound $\vdash t$ wrt $\models$:

**Lemma 6.** If $\Gamma; P \vdash t : W \rightsquigarrow (p, \sigma)$ then $MV(\Gamma, p) \models [W] := P \Rightarrow (\sigma, W)$

**Proof.** By induction on the assumed derivation

**Case ?Head** Our assumed derivation is

$$\neg App(t) \quad \Gamma \models t : T \rightsquigarrow e \quad \emptyset \models [T] := ? \Rightarrow P \Rightarrow (\sigma_{id}, W)$$

We apply Lemma 5 on the third hypothesis to get

$$MV(\Gamma, e) = \emptyset \models [W] :=? \Rightarrow P \Rightarrow (\sigma_{id}, W)$$

which is what we need.

**Case ?TApp** Our assumed derivation is

$$\Gamma; ? \Rightarrow P \models t : \forall X = R. W \rightsquigarrow (p, \sigma) \quad R \in \{X, S\}$$

$$\Gamma; ? \Rightarrow P \models t[S] : [S/X] W \rightsquigarrow (p[S], \sigma)$$

The only rule which allows us to form this conclusion is MForall, with premise $MV(\Gamma, p) \models [W] :=? \Rightarrow (\sigma, W)$

The derivation of $\models$ implies (implicitly) that $[S/X] W$ is defined, and it is clear that $\sigma \circ [R/X](X) \in \{X, S\}$, so by Lemma 8 (validity of using substitutions on matches) we have


allowing us to complete the proof.

**Case ?App** Our assumed derivation is

$$\Gamma; ? \Rightarrow P \models t : W \rightsquigarrow (p, \sigma) \quad \Gamma \models (p: W, \sigma) \cdot t' : W' \rightsquigarrow (p', \sigma')$$

$$\Gamma; P \models t \cdot t' : W' \rightsquigarrow (p', \sigma')$$

By the IH on the first premise, we have

$$MV(\Gamma, p) \models [W] :=? \Rightarrow (\sigma, W)$$

With this and with the second premise, we appeal to Lemma 9 (algorithmic application preserves matching) to conclude

$$MV(\Gamma, p') \models [W'] := P \Rightarrow (\sigma, W')$$

3.6 Lemma: Matches generate well-formed Decorations

**Lemma 7.** If $X \models [T] := P \Rightarrow (\sigma, W)$ with $WF(\Gamma, P)$ and $WF((\Gamma, X), T)$ then for all $X \in \overline{X}$, $\sigma(X) = X$ or $WF(\Gamma, \sigma(X))$.

**Proof.** By a simple inductive argument on the assumed derivation. First, note that after a base-case is formed using rules MType, M?, or MCurr, the generated solution decreases in its domain with each inductive use of MForall, so we need only consider the base cases. Next, base cases M? and MCurr produce $\sigma_{id}$, and the property we are trying to prove holds trivially for the empty solution. The only case of interest, then, is MType.

MType tells us that our assumed prototype $P$ is some type $S$, so by assumption $WF(\Gamma, S)$. This means that in the substitution we produce, $[U/Y]$, the free type variables in the codomain $(FV(U))$ do not overlap with any meta-variables. Furthermore, free
type variables in $\overline{U}$ cannot be confused with bound type variables in $S$ thanks to the second condition, so the only free type variables in $\overline{U}$ must be those declared in $\Gamma$ – giving us $WF(\Gamma, \overline{U})$.

### 3.7 Lemma: Substitutions on Matches

**Lemma 8.** If $\overline{X}, X \vdash^{\#} T := P \Rightarrow (\sigma, W)$, $[S/X]W$ is defined, and $\sigma(X) \in \{X, S\}$, and there is some $\Gamma$ such that $WF(\Gamma, S)$ and $WF(\Gamma, P)$, then $\overline{X} \vdash^{\#} [S/X]T := P \Rightarrow (\sigma - X, [S/X]W)$

**Proof.** By a simple inductive argument on the assumed derivation. The only interesting cases are the two base cases of the match $MCurr$ (which works because by assumption $[S/X]W$ is defined) and $MType$. For $MType$ we have

$$\begin{align*}
\forall \gamma, X \vdash \gamma \Rightarrow T := S \Rightarrow ([\gamma]/Y, W) \\
\end{align*}$$

We have two subcases to consider, corresponding the assumption that $[\gamma](X) \in \{X, S\}$. If $[\gamma](X) = X$ then clearly $X \notin Y$ and $[S/X]T = T$, and we can easily modify the above derivation to

$$\begin{align*}
\forall \gamma, X \vdash [S/X]T := T' \Rightarrow ([\gamma]/Y, [S/X]W) \\
\end{align*}$$

If $[\gamma](X) = S$ then we can easily factor out the mapping $[S/X]$ and similarly get the same derivation. 

### 3.8 Lemma: $\vdash^\#$ is sound wrt Matching

**Lemma 9.** If $MV(\Gamma, p) \vdash^{\#} [W] := ? \Rightarrow P \Rightarrow (\sigma, W)$ and $\Gamma \vdash^\# (p : W, \sigma) \cdot t' : W' \rightsquigarrow (p', \sigma')$ then $MV(\Gamma, p') \vdash^{\#} [W'] := P \Rightarrow (\sigma, W')$

**Proof.** By induction on the assumed derivation of $\vdash^\#$.

**Case $\forall$Forall:** Our assumed derivation is

$$\begin{align*}
\sigma'' &= \text{if } R = X \text{ then } \sigma \text{ else } R[X] \circ \sigma \\
\Gamma \vdash^\# (p : W, \sigma) \cdot t' : W' \rightsquigarrow (p', \sigma') \\
\Gamma \vdash^\# (p : \forall X = R.W, \sigma) \cdot t' : W' \rightsquigarrow (p', \sigma') \Rightarrow (\sigma'', W) \\
\end{align*}$$

And our assumed match is

$$MV(\Gamma, p) \vdash^{\#} \forall X. [W] := ? \Rightarrow P \Rightarrow (\sigma, \forall X = R.W)$$

Now, the only rule that could have formed this match (by inversion) is rule $MForall$, whose premise is

$$MV(\Gamma, p[X]) \vdash^{\#} [W] := ? \Rightarrow P \Rightarrow (\sigma'', W)$$

This is the match we need to invoke the IH on the derivation of $\vdash^\#$ in the premise of our assumption – the IH gives us

$$MV(\Gamma, p) \vdash^{\#} [W'] := P \Rightarrow (\sigma', W')$$

which is what we need to conclude.

**Case $\forall$Chk:** Our assumed derivation is

$$\begin{align*}
MV(\Gamma, \sigma) S &= \emptyset \\
\Gamma \vdash^\# t' : S \rightsquigarrow e \\
\Gamma \vdash^\# (p : S \to W, \sigma) \cdot t' : W \rightsquigarrow (p e', \sigma) \Rightarrow (\sigma', W') \\
\end{align*}$$

and our assumed match is

$$MV(\Gamma, p) \vdash^{\#} S \to [W] := ? \Rightarrow P \Rightarrow (\sigma, S \to W)$$

By inversion, the only rule introducing this match is $MArr$ whose premise is

$$MV(\Gamma, p) \vdash^{\#} [W] := P \Rightarrow (\sigma, W)$$

which is what we need to conclude!
Case \( ?\text{Syn} \): Our assumed derivation is
\[
\frac{\text{MV}(\Gamma, \sigma, S) = \emptyset \neq \emptyset \quad \Gamma \vdash_{\delta} t : \nu[\nu/\nu] \quad \sigma, S \rightsquigarrow e}{\Gamma \vdash (p : S \rightarrow W, \sigma) \cdot t' : \nu[\nu/\nu] \quad W \rightsquigarrow ((\nu[\nu/\nu] p) e', \sigma)}
\]

and our assumed match is
\[
\text{MV}(\Gamma, p) \vdash_{=} S \rightarrow \nu[\nu] := ? \rightarrow P \Rightarrow (\sigma, S \rightarrow W)
\]

By inversion, the only rule introducing this match is \( \text{MArr} \) whose premise is
\[
\text{MV}(\Gamma, p) \vdash_{=} \nu[\nu] := P \Rightarrow (\sigma, W)
\]

By Lemma \( \square \) (substitutions on matches) we can rewrite this match to
\[
\text{MV}(\Gamma, \nu[\nu] p) \vdash_{=} \nu[\nu] \nu[\nu] W := \Rightarrow (\sigma, \nu[\nu] W) \text{ since}
\]
- \( \nu[\nu] W \) is defined
- For all \( Y \in \nu[\nu] \), \( \sigma(Y) = Y \)
- \( \text{WF}(\Gamma, S) \) and \( \text{WF}(\Gamma, P) \) by (implicit) assumption
- \( \sigma \neq \nu[\nu] = \sigma \), by the definition of \( \nu[\nu] \)

This is precisely the match we need to conclude.

\[ \square \]

4 Completeness of \( \vdash_{\delta} \) wrt \( \vdash_{\delta} \)

1. If \( \Gamma \vdash_{\delta} t : T \rightsquigarrow e \) then \( \Gamma \vdash_{\delta} t : T \rightsquigarrow e \)

2. If \( \Gamma \vdash P \quad t : T \rightsquigarrow (p^+, \sigma) \)

and \( \text{MV}(\Gamma, p^+) \vdash_{=} T^+ := P \Rightarrow (\sigma^A, W^+) \), where

\begin{itemize}
  \item \( \sigma \subseteq \sigma^A \)
  \item \( \text{arr}_P(P) \geq 1 \) when \( \neg \text{App}(t) \)
\end{itemize}

then there exists \( (p, T, W, \sigma^+) \) where

\begin{itemize}
  \item \( \text{MV}(\Gamma, p) \vdash_{=} T := P \Rightarrow (\sigma^A \circ \sigma^+, W) \)
  \item \( \sigma^+(p, T, W) = (p^+, T^+, W^+) \) and \( \text{dom}(\sigma^+) = \text{MV}(\Gamma, p) - \text{MV}(\Gamma, p^+) \)
  \item \( \Gamma; P \vdash_{\delta} t : W \rightsquigarrow (p, \sigma^A \circ \sigma^+) \)
\end{itemize}

3. If \( \Gamma \vdash (p^+ : T^+, \sigma) \cdot t' : T^+ \rightsquigarrow (p'\cdot, \sigma') \) where

\begin{itemize}
  \item \( \text{MV}(\Gamma, p'^+) \vdash_{=} T'^+ := P \Rightarrow (\sigma'^A, W'^+) \) with \( \sigma' \subseteq \sigma'^A \)
  \item \( \text{MV}(\Gamma, p) \vdash_{=} ? := P \Rightarrow (\sigma^A \circ \sigma^+, W) \) with \( \sigma \subseteq \sigma^A \)
  \item and \( \sigma^+(p, T) = (p^+, T^+) \)
\end{itemize}

then there exists \( (p', T', W', \sigma'^+) \) where

\begin{itemize}
  \item \( \text{MV}(\Gamma, p') \vdash_{=} T' := P \Rightarrow (\sigma'^A \circ \sigma'^+, W') \) with \( \sigma' \subseteq \sigma'^A \)
  \item \( \sigma'^+(p', T', W') = (p'^+, T'^+, W'^+) \), \( \text{dom}(\sigma'^+) = \text{MV}(\Gamma, p') - \text{MV}(\Gamma, p'^+) \)
  \item and \( \Gamma \vdash (p : W, \sigma^A \circ \sigma^+) \cdot t' : W' \rightsquigarrow (p', \sigma'^A \circ \sigma'^+) \)
\end{itemize}

4.1 Complete \( \vdash_{\delta} \) wrt \( \vdash_{\delta} \)

Theorem 7. If \( \Gamma \vdash_{\delta} t : T \rightsquigarrow e \) then \( \Gamma \vdash_{\delta} t : T \rightsquigarrow e \).

Proof. By induction on the assumed derivation. The rules for the two systems are identical except for \( \text{AppSyn} \) and \( \text{AppChk} \), so only these are shown.

\footnote{The superscript \(^+\) denotes only that the terms and types of the declarative system have some additional substitutions \( \sigma^+ \) in them that the algorithmic rules would not have made.}
Case \textit{AppSyn} Our assumed derivation is

\[
\Gamma \vdash^T t \cdot T \leadsto (e, \sigma_{id}) \quad MV(\Gamma, T) = MV(\Gamma, e) = \emptyset
\]

\textit{AppSyn}

To invoke mutual induction on the completeness of \textit{\vdash^?}, we must provide a match. This would be

\[
\emptyset \vdash^? T := \sigma \Rightarrow (\sigma_{id}, T) \quad M?\
\]

It is immediate that the two precondition hold for the substitution \( - \sigma_{id} \subseteq \sigma_{id} \). We now invoke complete \textit{\vdash^?} (instantiating \( \sigma_{id} \) for \( \sigma^A \)) to get \( (p, T, W, \sigma^+) \) where

- \( MV(\Gamma, p) \vdash^? T := ? \Rightarrow (\sigma^+, W) \)
  
  The only rule which forms a match like this (by inversion) is \( M? \). From this we know that \( \sigma^+ = \sigma_{id} \).

- \( \sigma^+(p, T, W) = (e, T', T') \)
  
  This gives us \( (p, T, W) = (e, T', T') \).

- \( \Gamma; ? \vdash^? t : W \leadsto (p, \sigma^A \circ \sigma^+) \)
  
  which we rewrite to \( \Gamma; ? \vdash^? t : T' \leadsto (e, \sigma_{id}) \).

We conclude

\[
\Gamma \vdash^? t \cdot T' \leadsto (p, \sigma_{id}) \quad MV(\Gamma, p) = \emptyset
\]

\textit{AppSyn}

Case \textit{AppChk}: Our assumed derivation is

\[
\Gamma \vdash^P t \cdot T' \leadsto (p^+, \sigma) \quad MV(\Gamma, p^+) = MV(\Gamma, T^+) = dom(\sigma)
\]

\textit{AppChk}

To invoke mutual induction on the completeness of \textit{\vdash^?}, we must provide a match. This would be

\[
\frac{MV(\Gamma, T^+) = \text{FV}(T) \cap MV(\Gamma, p^+) = \text{FV}(\text{cod}(\sigma)) \cup (\text{BTV}(\sigma \cdot T^+) \cup MV(\Gamma, p^+)) = \emptyset}{\text{MTtype}}
\]

(The second condition we get from the stronger result of Lemma[1], that solutions in \( \sigma \) are well-formed wrt \( \Gamma \)). It is clear that this match satisfies the precondition for Theorem[8] (the completeness of \( \vdash^? \)), so we invoke it (mutually-inductively) to get \( (p, T, W, \sigma^+) \) where

- \( MV(\Gamma, p) \vdash^? T := \sigma \cdot \sigma^+ \Rightarrow (\sigma \circ \sigma^+, W) \)
  
  The only matching rule that could give us this conclusion is \textit{MTtype}, which tells us \( W = T \).

- \( \sigma^+(p, T, W) = (p^+, T^+, T^+) \) and \( \text{dom}(\sigma^+) = MV(\Gamma, p) - MV(\Gamma, p^+) \)
  
  This allows us to derive \( MV(\Gamma, p) = MV(\Gamma, T) = \text{dom}(\sigma \circ \sigma^+) \).

- \( \Gamma; T \vdash^? t : T' \leadsto (p, \sigma \circ \sigma^+) \)

We can therefore conclude

\[
\frac{\Gamma; T \vdash^? t \cdot T' \leadsto (p, \sigma \circ \sigma^+) \quad MV(\Gamma, p) = \text{dom}(\sigma \circ \sigma^+)}{\text{AppChk}}
\]

\( \square \)

4.2 Complete \( \vdash^? \) wrt \( \vdash^P \)

Theorem 8. If \( \Gamma \vdash^P t : T' \leadsto (p^+, \sigma) \) and \( MV(\Gamma, p^+) \vdash^? T^+ := P \Rightarrow (\sigma^A, W^+) \), where

- \( \sigma \subseteq \sigma^A \)
- \( \text{arr}_P(P) \geq 1 \) when \( \neg \text{App}(t) \)

then there exists \( (p, T, W, \sigma^+) \) where

- \( MV(\Gamma, p) \vdash^? T := P \Rightarrow (\sigma^A \circ \sigma^+, W) \)
• $\sigma^+(p,T,W) = (p^+,T^+,W^+)$, $dom(\sigma^+) = MV(\Gamma, p) - MV(\Gamma, p^+)$

• $\Gamma; P \vdash t : W \rightsquigarrow (p, \sigma^A \circ \sigma^+)$

Proof. By induction on the assumed derivation.

Case $\textit{Head}$: Our assumed derivation is

$$\neg \text{App}(t) \quad \Gamma \vdash t : T \rightsquigarrow e \quad \text{Head}$$

and our assumed match is $MV(\Gamma, e) \vdash T := ? \Rightarrow (\sigma^A, W)$

Since we know $e$ is well-typed under $\Gamma$, $MV(\Gamma, e) = \emptyset$. Appealing to Lemma 10 we get $dom(\sigma^A) \subseteq \emptyset$, so $\sigma^A = \sigma_{id}$. We rewrite our match to

$\emptyset \vdash T := ? \Rightarrow (\sigma_{id}, W)$

Now, invoke mutual induction on the completeness of $\vdash_\emptyset$ (Theorem 7) to get

$\Gamma \vdash t : T \rightsquigarrow e$

and choose $(e, T, W, \sigma_{id})$ to meet the desired derivation and conditions

• $MV(\Gamma, e) \vdash T := ? \Rightarrow (\sigma_{id}, W)$

• $\sigma_{id}(e, T, W) = (e, T, W)$,

• $\Gamma; ? \Rightarrow P \vdash t : W \rightsquigarrow (e, \sigma_{id})$

Case $\textit{TApp}$: Our assumed derivation is

$$\Gamma \vdash \forall X. T^+ \rightsquigarrow (p^+, \sigma)$$

$$\Gamma \vdash t[S] : [S/X]T^+ \rightsquigarrow (p^+[S], \sigma)$$

$\text{ITApp}$

and our assumed match is

$MV(\Gamma, p^+[S]) \vdash [S/X]T^+ := ? \Rightarrow (\sigma^A, [S/X]W^+)$

We appeal to Lemma 11 (invertible substitutions in matching) to get

$MV(\Gamma, p^+[S]), X \vdash T^+ := ? \Rightarrow (\sigma^A \circ \sigma_X, W_X^+)$

where

• $\sigma_X \subseteq [S/X]$

That is, $\sigma_X(X) \in \{X, S\}$

• $[S/X]W_X^+ = W^+$

With that match, we now can apply matching rule $\text{MForall}$ to get

$MV(\Gamma, p[S]) \vdash \forall X. T^+ := ? \Rightarrow (\sigma^A, \forall X = \sigma_X(X), W^+)$

Lastly, we note that $MV(\Gamma, p[S]) = MV(\Gamma, p)$, so we are able to invoke the IH to get $(p, T, W, \sigma^+)$ where

• $MV(\Gamma, p) \vdash T := ? \Rightarrow (\sigma^A \circ \sigma^+, W)$

• $\sigma^+(p, T, W) = (p^+, \forall X. T^+, \forall X = \sigma_X(X), W^+)$

and $dom(\sigma^+) = MV(\Gamma, p) - MV(\Gamma, p^+)$

• $\Gamma; ? \Rightarrow P \vdash t : W \rightsquigarrow (p, \sigma^A \circ \sigma^+)$

Before we can finish the derivation of $\textit{TApp}$ we must deal with a subtle issue – what if $T = Y$ and $W = (Y, {? \Rightarrow P})$, with $\sigma^+(Y) = \forall X = \sigma_X(X), W^+$? This would prevent the algorithmic rules from inferring a type application, and we’d be stuck!

Fortunately, we need only look at the match and equality produced by the the result of calling the IH to sort this out. If $T = Y$ then it could only be formed by $MCurr$, yielding

$MV(\Gamma, p) \vdash Y := ? \Rightarrow (\sigma^A \circ \sigma^+ = \sigma_{id}, (Y, {? \Rightarrow P}))$

But now it’s impossible that $\sigma^+(Y) = \forall X = \sigma_X(X), W^+$. Therefore, we know that $T$ has the form $\forall X. T$ (we shadow the original $T$ from here on out) and revisit our conclusions
• $MV(\Gamma, p) \vdash: \forall X. T := ? \Rightarrow P \Rightarrow (\sigma^A \circ \sigma^+, \forall X = R.W)$

• $\sigma^+(p, \forall X. T, \forall X = R.W) = (p^+, \forall X. T^+, \forall X = \sigma_X(X), W^+)$

and $dom(\sigma^+) = MV(\Gamma, p) - MV(\Gamma, p^+)$

We therefore know that $R = \sigma_X(X)$

• $\Gamma; ? \Rightarrow P \vdash\Rightarrow t : \forall X = R.W \rightsquigarrow (p, \sigma^A \circ \sigma^+)$

This allows us to conclude

$\Gamma; ? \Rightarrow P \vdash\Rightarrow t[S] : [S/X]W \rightsquigarrow (p[S], \sigma^A \circ \sigma^+)$

**Case** ?App: Our assumed derivation is

\[
\frac{\Gamma \vdash p : T^+ \rightsquigarrow (p^+, \sigma) \quad \Gamma \vdash (p^+: T^+, \sigma) \cdot t' : T'^+ \rightsquigarrow (p'^+, \sigma')} {\Gamma \vdash p \cdot t' : T'^+ \rightsquigarrow (p'^+, \sigma')}
\]

Our assumed match is

$MV(\Gamma, p'^+) \vdash: T'^+ := P \Rightarrow (\sigma'^A, W'^+)$

By Lemma 13 (application of partially synthesized applicands preserves matching backwards) we get from this and the second premise of the derivation

$MV(\Gamma, p^+) \vdash: T^+ := ? \Rightarrow P \Rightarrow (\sigma^A, W^+)$, with $\sigma \subseteq \sigma^A$.

This allows us to invoke the IH on the first premise of the derivation to get $(p, T, T^+, \sigma^+)$ where

• $MV(\Gamma, p) \vdash: T := ? \Rightarrow P \Rightarrow (\sigma^A \circ \sigma^+, W)$

• $\sigma^+(p, T, W) = (p^+, T^+, W^+)$ and $dom(\sigma^+) = MV(\Gamma, p) - MV(\Gamma, p^+)$

• $\Gamma; ? \Rightarrow P \vdash\Rightarrow t : W \rightsquigarrow (p, \sigma^A \circ \sigma^+)$

The first two of these conditions, and the match we assumed, satisfy the preconditions Theorem 9, allowing us to use mutual induction to get $(p', T', W', \sigma'^+)$ where

• $MV(\Gamma, p') \vdash: T' := P \Rightarrow (\sigma'^A \circ \sigma'^+, W')$ with $\sigma' \subseteq \sigma'^A$

• $\sigma'^+(p', T', W') = (p'^+, T'^+, W'^+), \quad dom(\sigma'^+) = MV(\Gamma, p') - MV(\Gamma, p'^+)$

• and $\Gamma \vdash (p : W, \sigma^A \circ \sigma^+) \cdot t' : W' \rightsquigarrow (p', \sigma'^A \circ \sigma'^+)$

This allows us to conclude $\Gamma; P \vdash\Rightarrow t' : W' \rightsquigarrow (p', \sigma'^A \circ \sigma'^+)$

\[\square\]

### 4.3 Complete \vdash \wrt \vdash

**Theorem 9. Completeness of the algorithm wrt the specification (applications):**

If $\Gamma \vdash (p^+: T^+, \sigma) \cdot t' : T'^+ \rightsquigarrow (p'^+, \sigma')$ where

• $MV(\Gamma, p^+) \vdash: T'^+ := P \Rightarrow (\sigma'^A, W'^+)$ with $\sigma' \subseteq \sigma'^A$

• and $MV(\Gamma, p) \vdash: T := ? \Rightarrow P \Rightarrow (\sigma^A \circ \sigma^+, W)$ with $\sigma \subseteq \sigma^A$

• and $\sigma^+(p, T, \sigma^+) = (p^+, T^+, \sigma^+)$, $\quad dom(\sigma^+) = MV(\Gamma, p) - MV(\Gamma, p^+)$

then exists $(p', T', W', \sigma'^+)$ where

• $MV(\Gamma, p') \vdash: T' := P \Rightarrow (\sigma'^A \circ \sigma'^+, W')$ with $\sigma' \subseteq \sigma'^A$

• $\sigma'^+(p', T', W') = (p'^+, T'^+, W'^+), \quad dom(\sigma'^+) = MV(\Gamma, p') - MV(\Gamma, p'^+)$

• and $\Gamma \vdash (p : W, \sigma^A \circ \sigma^+) \cdot t' : W' \rightsquigarrow (p', \sigma'^A \circ \sigma'^+)$

**Proof.** By a (not-so-easy) induction on the assumed derivation.
Our assumed derivation is
\[
\sigma'' \in \{\sigma, [S/X] \circ \sigma\}, \quad W.F(\Gamma, S) \quad \Gamma \vdash (p^+[X] : T^+, \sigma'') \cdot t' : T'^+ \rightsquigarrow (p', \sigma') \quad \text{PForall}
\]

Our assumed conditions are
- \(MV(\Gamma, p^+) \models^\vdash T'^+ := P \Rightarrow (\sigma'^A, W^+)\) with \(\sigma' \subseteq \sigma'^A\)
- and \(MV(\Gamma, p) \models^\vdash T := ? \Rightarrow (\sigma^A \circ \sigma^+, W)\) with \(\sigma \subseteq \sigma^A\)
- and \(\sigma^+(p, T) = (p^+, \forall X, T^+), \text{dom}(\sigma^+) = MV(\Gamma, p) - MV(\Gamma, p^+)\)

To make progress we need some way to reveal that \(T \neq Y\) for some \(Y \in MV(\Gamma, p)\) – because if it were, then we would not be able to apply the algorithmic rule \(\text{PForall}\). First, we note that it is easy to show (Lemma 18) that \(\forall X, T^+\) being in the application position of a judgment of \(\vdash\), it must really have the following form
\[
\forall X, X, S^+ \rightarrow T'^+.
\]

(The reason for subscript \(Y\) will become apparent a little later). By a similar observation (a kind of “peek-ahead” assumed derivation of \(\vdash\), Lemma [19] tells us that the base-case for our assumed derivation of \(\vdash\) generates some substitution \(\sigma_Y\), where \(\text{dom}(\sigma_Y) \subseteq Y \subseteq MV(\Gamma, \sigma [p[X][\overline{X}]]), \text{such that}\ \sigma_Y T'^+_Y = T'^+\)

Returning to our troubles, if \(T = Y\) then the second of our assumed matches must have been formed by rule \(\text{MCurr}\), which tells us
\[
MV(\Gamma, p) \models^\vdash Y := ? \Rightarrow P \Rightarrow (\sigma^A \circ \sigma^+ = \sigma_{id}, (Y, ? \Rightarrow P) = W)
\]

However, our third condition tells us that \(\sigma^+(Y) = \sigma_{id}(Y) = \forall X, X, S^+ \rightarrow T'^+_Y\) – which is impossible! We can iterate this argument over each bound variable in \(\overline{X}\) to get, finally, that \(T\) looks like \(\forall X, \overline{X}, S \rightarrow T^+_Y\) for some \(S\) and \(T^+_Y\). Knowing this, we revisit the second and third assumed conditions on our derivation:
- \(MV(\Gamma, p) \models^\vdash \forall X, \overline{X}, S \rightarrow T^+_Y := ? \Rightarrow P \Rightarrow (\sigma^A \circ \sigma^+, \forall X, \overline{X} = R, R, W^+_Y)\)
  - with \(\sigma \subseteq \sigma^A\), and for some \(W^+_Y \subseteq R\), and \(R\)
- and \(\sigma^+(p, \forall X, \overline{X}, S \rightarrow T^+_Y) = (p^+, \forall X, \overline{X}, S^+ \rightarrow T^+_Y),\)
  - \(\text{dom}(\sigma^+) = MV(\Gamma, p^+) - MV(\Gamma, p)\)

We next need some way to relate the specificational system’s “guess” \(\sigma''(X)\) with the match-generated decoration \(R\). Our algorithmic rules will first want to define \(\sigma'^A = \text{if } R = X \text{ then } \sigma^A \text{ else } [R/X] \circ \sigma^A\). To satisfy the precondition on the IH, we need to show that \(\sigma'^A \subseteq \sigma'^{\overline{A}}\). As \(\sigma \subseteq \sigma^A\), this reduces to showing that if \(\sigma''(X) = S\) then \(\sigma'^{\overline{A}}(X) = S\).

\(\sigma''\) and \(\sigma'^{\overline{A}}\): By an easy inductive argument we know that \(\vdash\) grows its generated solutions monotonically, so the derivation in the premise of our assumption,
\[
\Gamma \vdash (p^+[X] : T^+, \sigma'') \cdot t' : T'^+ \rightsquigarrow (p', \sigma')
\]
tells us that \(\sigma'' \subseteq \sigma'\), and furthermore by assumption \(\sigma' \subseteq \sigma'^A\) If the specificational rules guessed \(S\), then it is clear that \(\sigma'^A(X) = S\).

Next, since we have that \(T'^+ = \sigma^+ \sigma_Y T'^+_Y\), the match in our first condition is
\[
MV(\Gamma, p'^+) \models^\vdash \sigma^+ \sigma_Y T'^+_Y := P \Rightarrow (\sigma'^A, W'^+)
\]

We invoke Lemma [1][invertible substitutions in matches] to get
\[
MV(\Gamma, p^+), Y \models^\vdash T^+_Y := P \Rightarrow (\sigma'^A \circ \sigma'', W^+_Y) \quad (\text{for some } \sigma'' \subseteq \sigma^+ \circ \sigma_Y).
\]

which we can repack into (successively using rule \(\text{MForall}\))
\[
MV(\Gamma, p) \models^\vdash \forall X, \overline{X}, S \rightarrow T^+_Y := ? \Rightarrow P \Rightarrow (\sigma^A \circ \sigma^+, \forall X, \overline{X} = R, R, S \rightarrow W^+_Y)
\]
(re-use of meta-variables \(\sigma^A\), \(\sigma^+\) is justified by Lemma [15] and the match from our second assumed condition). Well, if \(\sigma''(X) = S\), then \(\sigma'^A(X) = R = S\). And since \(R = S\), the algorithmic rules must choose \(\sigma'^A = [S/X] \circ \sigma^A\), meaning that \(\sigma'^A(X) = S\) as well, giving us that \(\sigma'' \subseteq \sigma'^{\overline{A}}\).
IH: To recap, we now meet the desired preconditions to invoke the IH

- $MV(\Gamma, p^+ : T^+) = (\sigma^A, W^+)$ with $\sigma' \subseteq \sigma^A$
  
  This remains unmodified from our assumption

- and $MV(\Gamma, p[X]) = (\forall X, \exists S, T := p \Rightarrow (\sigma''^A \circ \sigma^+, \forall X = R, S \rightarrow W_T)$ with $\sigma'' \subseteq \sigma''^A$

- and $\sigma^+(p[R], T) = (p^+[R], T^+)$

We invoke the IH to get $(p^+, T', W', \sigma^+)$ where

- $MV(\Gamma, p^+) = (\sigma^A, W')$ with $\sigma' \subseteq \sigma^A$

- $\sigma^+(p^+, T', W') = (p^+, T', W'^+)$, $dom(\sigma^+) = MV(\Gamma, p^+) - MV(\Gamma, p^+)$

- and $\Gamma \vdash (p[X] : W, \sigma''^A \circ \sigma^+) \cdot t : W' \rightarrow (p^+, \sigma^A \circ \sigma^+)$

  which is what we need to derive

$\Gamma \vdash (p : \forall X, \exists S, T := p \Rightarrow (\sigma''^A(X), R, S \rightarrow W_T) \cdot t : W' \rightarrow (p^+, \sigma^A \circ \sigma^+))$

Case $PChk$ Our assumed derivation is

$\Gamma \vdash (p^+: S^+ \rightarrow T^+, \sigma^+) \cdot t^+ : T^+ \rightarrow (p^+, e', \sigma)$

Our assumed conditions are

- $MV(\Gamma, p^+ e) = (\sigma^A, W^+)$ with $\sigma' \subseteq \sigma^A$

- and $MV(\Gamma, p) = (\sigma^A, \sigma^+, S \rightarrow W)$ with $\sigma \subseteq \sigma^A$

  Again, reasoning (using the equality directly below) that the subject of this match could not be some $Y \in MV(\Gamma, p)$, it must be of the form $S \rightarrow T$

- and $\sigma^+(p, S \rightarrow T) = (p^+, S^+ \rightarrow T^+)$

We must now pick out a suitable $(\sigma^+, p^+, T', W')$ to provide as the result of this case. Pick $(\sigma^+, p \in T, W)$. Now we show the post-conditions of the theorem hold.

- $MV(\Gamma, p^+ e') = (\sigma^A \circ \sigma^+, W)$

  From the match given in our second assumed condition it is clear that

$MV(\Gamma, p^+ e') = (\sigma^A \circ \sigma^+, W)$

(because the only rule that could form it, $MArr$, would have this as its premise). Aligning this with our requirement reduces to showing that $\sigma^A = \sigma^A$. By Lemma [14] on the soundness of solutions by the matching, for the matching, we have

$MV(\Gamma, p^+ e') = (\sigma^A, \sigma^+, W)$

and comparing to our first condition, uniqueness of matching solutions (Lemma [15]) gives us

$\sigma^A = \sigma^A$ and $\sigma^+ W = W'^+$

- $\sigma^+(p^+ e', T, W) = (p^+ e', T^+, W'^+)$, $dom(\sigma^+) = MV(\Gamma, p \in e') - MV(\Gamma, p^+ e')$,

  Directly from assumptions and the equation in the point above, and from the fact that $MV(\Gamma, e') = \emptyset$

- and $\Gamma \vdash (p : S \rightarrow W, \sigma^A \circ \sigma^+) \cdot t' : W \rightarrow (p^+ e', \sigma^A \circ \sigma^+)$

  For this we invoke mutual induction on the completeness of $\vdash$ (Theorem [7]) to get

$\Gamma \vdash \sigma^A \sigma^+ S \rightarrow e'$, noting that $\sigma^+ S = S^+$ and $MV(\Gamma, \sigma^A S^+) = \emptyset$

which is what we need to conclude
Case \( PSyn \) Our assumed derivation is

\[
\begin{align*}
\Gamma \vdash (p^+ : S^+ \to T^+, \sigma) \cdot t' : [U/Y^+] T^+ \leadsto ([U/Y^+] p^+) e', \sigma
\end{align*}
\]

\( PSyn \)

Our assumed conditions are

- \( MV(\Gamma, [U/Y^+] p^+) \models [U/Y^+] T^+ := P \Rightarrow (\sigma^A, W^+T) \) with \( \sigma \subseteq \sigma^A \)
- and \( MV(\Gamma, p) \models S \to T := ? \to P \Rightarrow (\sigma^A \circ \sigma^+, S \to W) \) with \( \sigma \subseteq \sigma^A \)

Again, reasoning that the subject of this match must be \( S \to T \) and not some \( Y \in MV(\Gamma, p) \)

- and \( \sigma^+(p, S \to T) = (p^+, S^+ \to T^+) \)

We must pick a suitable \( (p', T', W', \sigma^+) \) for which we can derive a judgment formed by \( \models \) with the needed properties. To do this, we must first ask what we know about any unsolved meta-variables \( \Sigma \) that the \textit{algorithm} will encounter – \( MV(\Gamma, \sigma^A \sigma^+, S) = \Sigma \) – given that \( MV(\Gamma, \sigma S^+) = MV(\Gamma, \sigma \sigma^+ S) = \Sigma^+ \).

First, it is clear that \( \Sigma \subseteq \Sigma^+ \) because \( \sigma \subseteq \sigma^A \). So, consider the match from our first assumed condition. By Lemma 11 on inverting substitutions in the subject of a match, we get

\[
MV(\Gamma, p^+ e) \models := T^+ := P \Rightarrow (\sigma^A \circ \sigma_{\Sigma^+}, W_{\Sigma^+}), \text{ where } \sigma_{\Sigma^+}(W_{\Sigma^+}) = W^+
\]

Now, consider the match from our second assumed condition. By inversion we know it can only have been formed by \( MArr \), whose premise we further transform by Lemma 14 (re-substituting solutions in matches – in this case \( \sigma^+ \)) to get

\[
MV(\Gamma, p^+ e) \models := T^+ := P \Rightarrow (\sigma^A, \sigma^+ W)
\]

And now, by uniqueness of solutions of matching (Lemma 15) we get \( (\sigma^A, \sigma^+ W) = (\sigma^A \circ \sigma_{\Sigma^+}, W_{\Sigma^+}) \). Let us call, for the sake of simplicity, the second component of both pairs \( W^+ \), and let \( \sigma_{\Sigma^+} = [U/Y^+] - \sigma_{\Sigma^+} \)

We return to the task of selecting \( (p', T', W', \sigma^+) \). We pick

\[
((\sigma_{\Sigma^+} p) e', \sigma_{\Sigma^+} T, \sigma_{\Sigma^+} W, \sigma^+ \circ \sigma_{\Sigma^+})
\]

and now witness the following post-conditions:

- \( MV(\Gamma, p') \models := \sigma_{\Sigma^+} T := P \Rightarrow (\sigma^A \circ \sigma^+ \circ \sigma_{\Sigma^+}, \sigma_{\Sigma^+} W) \) with \( \sigma \subseteq \sigma^A \)

  This comes from the equational reasoning above, taking the match

  \[
  MV(\Gamma, p') \models := T := P \Rightarrow (\sigma^A \circ \sigma^+, W)
  \]

  noting that \( \sigma^A = \sigma^A \circ \sigma_{\Sigma^+} \) and deploying solution \( \sigma_{\Sigma^+} \) to \( T \) (Lemma 8), while then reasoning that \( dom(\sigma_{\Sigma^+}) \cap dom(\sigma^A \circ \sigma_{\Sigma^+}) = \emptyset \) (solution \( \sigma_{\Sigma^+} \) doesn’t interfere with the solutions the match generates) from the definition of \( \sigma_{\Sigma^+} \).
- \( \sigma^+(p', T', W') = (p^+, T^+, W'^+) \), \( dom(\sigma^+) = MV(\Gamma, p') - MV(\Gamma, p^+) \)

  Again with some equational reasoning. For example, \( \sigma^+ T' = \sigma^+ \sigma_{\Sigma^+} \sigma_{\Sigma^+} T = [U/Y^+] T^+ = T'^+ \)
- and \( \Gamma \vdash (p : W, \sigma^A \circ \sigma^+) \cdot t' : W' \leadsto (p', \sigma^A \circ \sigma^+) \)

This last piece requires some care – the algorithm might use more contextual information than the specificational derivation, meaning that we might need to derive \( ?Chk \) even though our assumed case is \( PSyn \). If \( \Sigma \neq \emptyset \), we know that the algorithm will try to derive

\[
\Gamma \vdash t : \sigma_{\Sigma^+} \sigma^A \sigma^+ S \leadsto e'.
\]

By an invocation of mutual induction on the completeness of \( \vdash \) (Theorem 7) on the second premise of our assumed derivation of \( \vdash \), we know that the algorithm can derive

\[
\Gamma \vdash t' : [U/Y^+] \sigma S^+ \leadsto e'
\]

which (by some equational reasoning) is what we need.

\(^2\)If you were wondering what the purpose was of \( \sigma^+ \) in these proofs, now you know – the specificational rules may opt to discover from synthetic type-argument inference what the algorithm would know from contextual type-argument inference.
However, if $\emptyset = \emptyset$, the algorithm will actually try to check the term $t'$ against a fully known type. We need

\[ \Gamma \vdash t' : \sigma^A \sigma^+ \vdash e' \]

By Lemma 10 (checking mode extends synthesizing mode) on the second premise of our assumed derivation we have

\[ \Gamma \vdash t' : [U/Y]^+ \sigma \vdash e' \]

By mutual induction on the completeness of $\vdash_{\downarrow}$ (Theorem 7) we get

\[ \Gamma \vdash \cdot \vdash_{\downarrow} (p : S \rightarrow W, \sigma^A \circ \sigma^+) \cdot t' : W' \vdash (p', \sigma'^A \circ \sigma'^+) \]

4.4 Lemma: Match solutions solve match meta-variables

Lemma 10.

If $\emptyset \vdash T := P \Rightarrow (\sigma, W)$ then $\text{dom}(\sigma) \subseteq X$

Proof. Straightforward induction on the assumed derivation.

4.5 Lemma: Invertible substitutions in matches

Lemma 11.

If $\emptyset \vdash [U/Y]^+ T := P \Rightarrow (\sigma, W)$ and $X \cap \text{FV}(U) = \emptyset$

then $X, Y \vdash [U/Y]^+ T := P \Rightarrow (\sigma \circ \sigma_Y, W_Y)$ where

- $\sigma_Y \subseteq [U/Y]$
- $[U/Y] W_Y = W$

Proof. By a straightforward inductive argument on the assumed derivation.

4.6 Lemma: $\vdash_{\downarrow}$ preserves $\vdash_{\downarrow} := \downarrow$ (forwards)

Lemma 12.

If $\emptyset \vdash (p : W, \sigma) \cdot t' : W' \vdash (p', \sigma')$ and $\text{MV}(\Gamma, p) \vdash [W] := ? \Rightarrow P \Rightarrow (\sigma, W)$

then $\text{MV}(\Gamma, p') \vdash [W'] := ? \Rightarrow P \Rightarrow (\sigma', W')$

Proof. By induction on the assumed derivation.

Case PForall: Our assumed derivation is

\[
\sigma'' = \begin{cases} R = X & \text{then } \sigma \text{ else } [R/X] \circ \sigma \\
\Gamma \vdash (p[X] : W, \sigma'') \cdot t' : W' \vdash (p', \sigma') \\ \Gamma \vdash (p : \forall X = R, W, \sigma) \cdot t' : W' \vdash (p', \sigma') \end{cases} \quad \text{PForall}
\]

and our assumed match is

\[ \text{MV}(\Gamma, p) \vdash_{\downarrow} \forall X. [W] := ? \Rightarrow P \Rightarrow (\sigma, \forall X = R, W) \]

The only rule giving us this match (by inversion) is MForall, with premise

\[ \text{MV}(\Gamma, p[X]) \vdash_{\downarrow} [W] := ? \Rightarrow P \Rightarrow (\sigma'', W) \]

We can now invoke the IH on the second premise of our assumed derivation to get

\[ \text{MV}(\Gamma, p') \vdash_{\downarrow} [W'] := P \Rightarrow (\sigma', W') \]

which is what we need to conclude.
**Case PChk:** Our assumed derivation is

\[ MV(\Gamma, \sigma S) = \emptyset \quad \Gamma \vdash t' : S \rightarrow e \]

\[ \Gamma \vdash (p : S \rightarrow W, \sigma) \cdot t' : W \rightarrow (p e', \sigma) \quad \text{PChk} \]

and our assumed match is

\[ MV(\Gamma, p) \vdash : S \rightarrow W, \sigma \rightarrow ((\overline{W}p) e', \sigma) \]

By inversion the only rule we can use to form this match is \( MArr \) with premise

\[ MV(\Gamma, p e') \vdash : S \rightarrow W, \sigma \rightarrow ((\overline{W}p) e', \sigma) \]

Since \( MV(\Gamma, e') = \emptyset \) this is what we need to conclude.

**Case PSyn:** Our assumed derivation is

\[ MV(\Gamma, \sigma S) = \overline{Y} \neq \emptyset \quad \Gamma \vdash t : [\overline{U}]/Y \quad \sigma S \rightarrow e \]

\[ \Gamma \vdash (p : S \rightarrow W) \cdot t' : [\overline{U}]/Y \rightarrow (((\overline{U}p) e') \rightarrow, \sigma) \quad \text{PSyn} \]

and our assumed match is

\[ MV(\Gamma, p) \vdash : S \rightarrow W, \sigma \rightarrow ((\overline{W}p) e', \sigma) \]

The only rule allowing us to form this match is \( MArr \), with premise

\[ MV(\Gamma, p e') \vdash : S \rightarrow W, \sigma \rightarrow ((\overline{W}p) e', \sigma) \]

By Lemma 8 and by noting that \( Y \cap \text{dom}(\sigma) = \emptyset \) from our first premise, we have

\[ MV(\Gamma, [\overline{U}]/p e') \vdash : [\overline{U}]/Y W := P \Rightarrow (\sigma, [\overline{U}]/Y W) \]

which allows us to conclude. \( \square \)

4.7 **Lemma:** \( \vdash \) preserves \( \vdash := \) (backwards)

**Lemma 13.**

If \( \Gamma \vdash (p : T, \sigma) \cdot t' : T' \rightarrow (p', \sigma) \) and \( MV(\Gamma, p') \vdash := T' := P \Rightarrow (\sigma', W') \)

then there exists \( (\sigma''', W) \) where \( MV(\Gamma, p) \vdash := T := ? \rightarrow P \Rightarrow (\sigma'''', W) \) and \( \sigma \subseteq \sigma''' \)

**Proof.** By induction on the assumed derivation of \( \vdash \).

**Case PForall** Our assumed derivation is

\[ \sigma'' \in \{ \sigma, \sigma \circ [S/X] \}, WF(\Gamma, S) \quad \Gamma \vdash (p[X] : T, \sigma'') \cdot t' : T' \rightarrow (p', \sigma') \]

\[ \Gamma \vdash (p : \forall X. T, \sigma) \cdot t' : T' \rightarrow (p', \sigma') \quad \text{PForall} \]

Our assumed match is

\[ MV(\Gamma, p) \vdash := T' := P \Rightarrow (\sigma'''', W') \]

where \( \sigma' \subseteq \sigma''' \)

We invoke the IH on this match and the second premise to get

\[ MV(\Gamma, p[X]) \vdash := T := ? \rightarrow P \Rightarrow (\sigma'''', W) \]

where \( \sigma'' \subseteq \sigma''' \)

Applying matching rule \( MForall \) gives us the desired result.

\[ MV(\Gamma, p) \vdash := \forall X. T := ? \rightarrow P \Rightarrow (\sigma'''', W) \]

\[ \text{Case PChk: } \quad \text{Our assumed derivation is} \]

\[ MV(\Gamma, \sigma S) = \emptyset \quad \Gamma \vdash t' : \sigma S \rightarrow e' \]

\[ \Gamma \vdash (p : S \rightarrow T, \sigma) \cdot t' : T \rightarrow (p e', \sigma) \quad \text{PChk} \]

Our assumed match is

\[ MV(\Gamma, p) \vdash := S \rightarrow [W] := \rightarrow P \Rightarrow (\sigma, W) \]
\(MV(\Gamma, p e') \models T := P \Rightarrow (\sigma'^A, W), \sigma \subseteq \sigma'^A.\)

We invoke matching rule \(MArr\) to conclude (noting \(MV(\Gamma, e') = \emptyset\))

\(MV(\Gamma, p) \models \top := T := P \Rightarrow (\sigma'^A, S \rightarrow W), \sigma \subseteq \sigma'^A.\)

**Case** \(PSyn\) Our assumed derivation is

\[
\frac{MV(\Gamma, \sigma S) = Y \neq \emptyset \quad \Gamma \vdash_\gamma t' : \frac{[U/Y]}{} \sigma S \leadsto e}{\Gamma \vdash (p : S \rightarrow T, \sigma) \cdot t' : \frac{[U/Y]}{} \sigma S \rightarrow W', \sigma \subseteq [U/Y]} PSyn
\]

Our assumed match is

\[
MV(\Gamma, \frac{[U/Y]}{} p e') \models \top := [U/Y] T := P \Rightarrow (\sigma'^A, S \rightarrow W'), \sigma \subseteq [U/Y]
\]

By Lemma 11 (invertibility of substitutions in a match), we have

\[
MV(\Gamma, \frac{[U/Y]}{} p e') \models \top := [U/Y] T := P \Rightarrow (\sigma'^A \circ \sigma Y, W'), \sigma Y \subseteq [U/Y]
\]

Noting that \(\sigma \subseteq \sigma'^A \subseteq \sigma'^A \circ \sigma Y\), we apply rule \(MArr\) to conclude

\[
MV(\Gamma, p e') \models \top := S \rightarrow T := \sigma'^A \circ \sigma Y, \sigma Y \subseteq [U/Y]
\]

\[\square\]

**4.8 Lemma: Match Solutions are Match Sound**

**Lemma 14.**

If \(X \models \top := T := P \Rightarrow (\sigma \circ \sigma', W)\) then \(X - \text{dom}(\sigma') \models \top := \sigma' T := P(\sigma, \sigma' W)\)

**Proof.** By an easy inductive argument on the assumed derivation. \[\square\]

**4.9 Lemma: Function-ness of Matching**

**Lemma 15.**

If \(X \models \top := T := P \Rightarrow (\sigma, W)\) and \(X \models \top := T := P \Rightarrow (\sigma', W')\),

then \((\sigma, W) = (\sigma', W')\)

**Proof.** By an easy inductive argument on the assumed derivation. \[\square\]

**4.10 Lemma: Checking extends Synthesizing**

**Lemma 16.**

If \(\Gamma \vdash_\gamma t : T \leadsto e\) then \(\Gamma \vdash_\gamma t : T \leadsto e\)

**Proof.** A mostly easy induction, given that many rules are “direction-polymorphic.” The only interesting case is \(AppSyn\), which we look more closely at now.

**Case** \(AppSyn\): Our assumed derivation is

\[
\frac{\Gamma \vdash t' : T' \leadsto e'}{\Gamma \vdash t' : T' \leadsto e'} \quad AppSyn
\]

But \(\text{dom}(\sigma_{id}) = \emptyset\) so we already have what we need:

\[
\frac{\Gamma \vdash t' : T' \leadsto (e, \sigma_{id}) \quad MV(\Gamma, e') = MV(\Gamma, T') = \emptyset}{\Gamma \vdash t' : \sigma_{id} T' \leadsto \sigma_{id} e'} \quad AppChk
\]

\[\square\]

**4.11 Lemma: Matching Arrows of \(P\) and \(W\):**

**Lemma 17.**

Let \(\text{arr}_P(P)\) be the number of prototype arrows prefixing \(P\), and \(\text{arr}_W(W)\) the number of decorated-type arrows preceding \(W\).

- If \(\Gamma; P \models \top : W \leadsto (p, \sigma)\) then \(\text{arr}_W(W) \leq \text{arr}_P(P)\)
• If $\Gamma \vdash e : T \Rightarrow (\sigma, W)$ then $arr_P(P) \leq arr_W(W)$

Proof. Straightforward:

• The first point is a special case of the third, by invoking Lemma 16.

• By an easy inductive argument on the assumed derivation of $\vdash e$, noting that the number of prototype and decorated arrows encountered during the inductive cases are equal up until the base case, in which they are either equal ($MType$ and $M?$) or the former is strictly greater than the latter ($MCurr$).

4.12 Lemma: Subject type reveals an arrow in $\vdash$.

Lemma 18.
If $\Gamma \vdash p : T \cdot t' : T' \Rightarrow (p', \sigma')$ then $T = \forall X. T''$ for some $T''$.

Proof. By a straightforward inductive argument on the assumed derivation. □

4.13 Lemma: Peek-ahead for $\vdash$.

Lemma 19.
If $\Gamma \vdash (p : \forall X. S \rightarrow T_{\forall}, \sigma) \cdot t' : T' \Rightarrow (p', \sigma')$ then there exists some $\sigma_{\forall}$ with $\forall Y \in MV(\Gamma, p) \cup X$ such that $\sigma_{\forall}(T_{\forall}) = T'$.

Proof. By a straightforward induction on the assumed derivation: in case $PChk \ Y = \emptyset$, and in case $PSyn \ \sigma_{\forall}$ comes from synthesizing the type of $e'$ and matching it against some expected type based on $T_{\forall}$ (and some guessing done in $PForall$). □

5 Qualified Completeness of $\vdash_{\delta}$ wrt $\vdash$

Definition 1. (Annotation Requirements for Typing the External Language): Let $e_P$ be a term of the internal language such that $\Gamma \vdash e_P : T_P$.

Furthermore, let $t_P$ be a term of the external language such that $t_P \in [e_P]$. We say that $t_P$ meets our annotation requirements when the following conditions hold for each sub-expression $e$ of $e_P$, corresponding sub-expression $t$ of $t_P$, and corresponding sub-derivation $\Gamma' \vdash e : T$ of a derivation of $\Gamma \vdash e_P : T_P$:

1. If $e = \lambda x : S. e'$ for some $S$ and $e'$, then $t = \lambda x : S. t'$ for some $t$.
2. If $e$ occurs as a maximal term application in $e_P$ and if $\Gamma' \vdash t : T' \Rightarrow (p, \sigma_{id})$ for some $T'$ and $p$, then $MV(\Gamma, p) = \emptyset$.
3. If $e$ is a term application and $t = t_1 \cdot t_2$ for some $t_1$ and $t_2$, and if $\Gamma' \vdash t_1 : T' \Rightarrow (p, \sigma_{id})$ for some $T'$ and $p$, then $T' = \forall X. S_1 \rightarrow S_2$ for some $S_1$ and $S_2$.
4. If $e$ is a type application and $t = t'[S]$ for some $t'$ and $S$, and $\Gamma' \vdash t' : T' \Rightarrow (p, \sigma_{id})$ for some $T'$ and $p$, then $T' = \forall X. S'$ for some $S'$.

If Definition 1 holds for some pair of internal and external terms $(e_P, t_P)$ then we can show the following theorems.

• If $e$ occurs somewhere in $e_P$ as not a term applicand, or if $\neg Ap(e)$, then $\Gamma' \vdash t : T \Rightarrow e$.

• If $e$ occurs as an applicand in $e_P$ and $e = e'[S]$ for some $e'$ and $S$, then $t = t'[S]$ for some $t'$, with $\neg TpApp(e')$, then $\Gamma' \vdash t : T' \Rightarrow (p, \sigma_{id})$ with some $\sigma$ such that $dom(\sigma) = MV(\Gamma, p)$ and $\sigma(p, T') = (e, T)$.

• If $TmApp(e)$ and $\Gamma \vdash e : T$ then $\Gamma' \vdash t : T \Rightarrow (p', \sigma_{id})$ with some $\sigma$ such that $dom(\sigma) = MV(\Gamma, p')$ and $\sigma(p', T) = (e, T')$.

• If

- $\Gamma \vdash e[(U_1, U_2)] : S' \rightarrow T'$ and $\Gamma \vdash t' : S' \Rightarrow e'$
- and some $\sigma$ with $dom(\sigma) = MV(\Gamma, p[X_1|X_2])$
- where $\sigma(p[X_1|X_2], S \rightarrow T) = (e[(U_1, U_2)], S' \rightarrow T')$
- and $((X_1, X_2)) = ((U_1, U_2))$

then

- $\Gamma \vdash (p[X_1]: \forall X_2. S \rightarrow T, \sigma_{id}) \cdot t' : T'' \Rightarrow (p', \sigma_{id})$
- with some $\sigma'$ with $dom(\sigma') = MV(\Gamma, p')$ and where $\sigma(p', T'') = (e[(U_1, U_2)], e', T')$

3The subscript $p$ indicates nothing more than an expression which we consider to be the whole program we are typing.
5.1 Qualified Completeness \( \vdash \) wrt \( \vdash \)

**Theorem 10.**
Under the qualifications of Definition\( \text{[1]} \), if \( e \) occurs as a non-applicand in \( e_P \) or if \( \neg \text{App}(e) \) then \( \Gamma \vdash \_ : T \rightsquigarrow e \)

**Proof.** By induction on the assumed derivation

**Case** \( \text{Var} \) Our assumed derivation is

\[
\Gamma \vdash x : \Gamma(x) \quad \text{Var}
\]

There is only one partial erasure of \( x - x \). We apply rule \( \text{Var} \) of \( \vdash \) to conclude

\[
\Gamma \vdash \_ : \Gamma(x) \rightsquigarrow x \quad \text{Var}
\]

**Case** \( \text{Abs} \) Our assumed derivation is

\[
\Gamma, x : T \vdash e : S \\
\Gamma \vdash \lambda x : T. e : T \rightarrow S \quad \text{AAbs}
\]

By our first assumed qualification, we have that our partial erasure \( t' \) of \( \lambda x : T. e \) has the form \( \lambda x : T. t \) for some partial erasure \( t \) of \( e \). We invoke the IH (the body of our \( \lambda \)-abstraction, \( e \), is not itself an applicand) and conclude

\[
\Gamma, x : T \vdash e : S \\
\Gamma, x : T \vdash \_ : e \quad \text{IH} \\
\Gamma \vdash \lambda x : T. t : T \rightarrow S \rightsquigarrow \lambda x : T. e \quad \text{AAbs}
\]

**Case** \( \text{TAbs} \) Our assumed derivation is

\[
\Gamma, X : T \vdash e : T \\
\Gamma \vdash \Lambda X. e : \forall X. T \quad \text{TAbs}
\]

We have a partial erasure \( \Lambda X. t \) of \( \Lambda X. e \), meaning that \( t \) is a partial erasure of \( e \). We invoke the IH to conclude

\[
\Gamma, X : T \vdash e \quad \text{IH} \\
\Gamma \vdash \Lambda X. t : \forall X. T \rightsquigarrow \Lambda X. e \quad \text{TAbs}
\]

**Case** \( \text{TApp} \) Our assumed derivation is

\[
\Gamma \vdash e : \forall X. T \\
\Gamma \vdash e[S] : [S/X]T \quad \text{TApp}
\]

By assumption, \( e[S] \) occurs somewhere not as a term-applicand* in \( e_P \). This means that its erasure \( t \) corresponding to the same position in \( t_P \) has form \( t'\_S \) by the definition of erasure (we only erase type arguments between term to term applications).

Because \( e[S] \) is not a term applicand*, neither is \( e[\_S \_] \). Therefore, we can invoke the IH to conclude

\[
\Gamma \vdash e : \forall X. T \\
\Gamma \vdash e[S] : [S/X]T \rightsquigarrow e[S] \quad \text{TApp}
\]

**Case** \( \text{App} \) Our assumed derivation is

\[
\Gamma \vdash e : S' \rightarrow T' \quad \Gamma \vdash e' : S' \quad \text{App}
\]

Since the elaborated expression in question is \( e \ e' \) we know that its erasure must be of the form \( t \ t' \). We invoke mutual induction for the qualified completeness of \( \vdash \) wrt applications to get

\[
\Gamma \vdash P \ t \ t' : T \rightsquigarrow (p, \sigma_{id}) \text{ with } \sigma \text{ such that} \\
\bullet \ \text{dom}(\sigma) = MV(\Gamma, p)
\]

\(^4\text{Recall the definitions of term applicand* earlier in the document}\)
σ(p,T) = (e',T')

Now, by assumption e' occurs as not a term applicand* in e_\_p. By qualification #2 we have MV(Γ, p) = ∅. We use this to rewrite the post-conditions of our invocation of mutual induction above:

• dom(σ) = MV(Γ, p) = ∅ ⇒ σ = σ_id
• σ(p,T) = σ_id(p,T) = (p,T) = (e',T')

We can now conclude

Γ ⊢ P t t' : T' ⇝ (e',σ_id) MV(Γ, e') = MV(Γ, T') = ∅

AppSyn

5.2 Qualified Completeness of ⊢ P wrt ⊢ (TApp)

Theorem 11. Under the qualifications of Definition 1, if e occurs as a term applicand* in e_\_p and e = e'[S] for some e' and S, and t = t'[S] for some t', with ¬TpApp(e'), then Γ ⊢ P t' : T' ⇝ (p,σ_id) with some σ such that dom(σ) = MV(Γ, p) and σ(p,T) = (e,T')

Proof. By induction on the length of S

Case [S] = ∅ Our assumed derivation is

Γ' ⊢ e : T'

By assumption, ¬TpApp(e). We therefore have that either TmApp(e) or else ¬App(e) In either case we can appeal to mutual induction on qualified completeness to conclude:

Subcase TmApp(e): We appeal to qualified completeness of ⊢ P for applications (Theorem 12) to get

Γ' ⊢ P t t' : T' ⇝ (p,σ_id) with σ s.t. dom(σ) = MV(Γ', p) and σ(p,T) = (e,T'), which is what we need to conclude.

Subcase ¬App(e): We appeal to qualified completeness of ⊢⇑ (Theorem 10) to get

Γ' ⊢⇑ t' : e

and using rule PHead we derive

Γ' ⊢ P t' : (e,σ_id)

noting that MV(Γ', e) = ∅ and σ_id(e,T') = (e,T'), which is what we need to conclude.

Case [S] = [S'][S] Our assumed derivation is

Γ ⊢ e[S'] : ∀ X.T'

Γ ⊢ e[S'] [S] : [S/X]T' TApp

By the IH we have

Γ ⊢ e[S'] : ∀ X.T' IH with σ such that

• dom(σ) = MV(Γ', p)
• σ(p,T) = (e[S'],∀ X.T')

By qualification #4 we have T = ∀ X.T''. By combining this with the second post-conditions from the IH we get σ T'' = T'. We derive

Γ ⊢ P t[S'] : ∀ X.T'' ⇝ (p,σ_id) PTApp

and note we can produce σ as the output substitutions, since
• \( \text{dom}(\sigma) = MV(\Gamma, p[S]) = MV(\Gamma, p) \)

• \( \sigma(p[S], [S/X]T^\sigma) = (\epsilon([S^\sigma],[S/X]T^\sigma) \)

\((\text{dom}(\sigma) \cap X = \emptyset \text{ and cod}(\sigma) \text{ is only those types well-formed under } \Gamma) \)

\[ \square \]

### 5.3 Qualified Completeness of \( \vdash^P \) wrt \( \vdash (\text{App}) \)

**Theorem 12.** Under the qualifications of Definition 1, if \( \text{Tm}.\text{App}(e) \) and \( \Gamma \vdash e : T^\prime \) then \( \Gamma \vdash^P t : T \rightsquigarrow (p, \sigma_{id}) \) with some \( \sigma \) such that \( \text{dom}(\sigma) = MV(\Gamma, p) \) and \( \sigma(p, T) = (e, T^\prime) \)

**Proof.** Directly. Our internal term is \( e \) and external term is \( t t^\prime \), and our assumed derivation is

\[ \Gamma \vdash e : S^\prime \rightarrow T^\prime \]

\[ \Gamma \vdash e : S^\prime \]

We can rewrite \( e = e''[\overline{U}] \), making visible all of the outmost type applications in \( e \) (if any). Since \( e \) is an applicand, we know that its erasure \( t \) may have had some number of the right-most type applications erased – so \( t = t''[\overline{U}] \) where \( \overline{U} = [\overline{U}_1][\overline{U}_2] \)

We examine the first premise of our assumed derivation. We now know it must have the following form:

\[ \Gamma \vdash e''[\overline{U}_1][\overline{U}_2] : \forall X.T^\prime_X \\
\Gamma \vdash e''[\overline{U}_1][\overline{U}_2] : S^\prime \rightarrow T^\prime \\
\Gamma \vdash e' : T^\prime \]

We appeal to mutual induction on the completeness of \( \vdash^P \) wrt \( \vdash (\text{Theorem 11}) \) to get:

\[ \Gamma \vdash^P t''[\overline{U}_1] : T^\prime_X \rightsquigarrow (p, \sigma_{id}) \] with \( \sigma \) such that

• \( \text{dom}(\sigma) = MV(\Gamma, p) \)

• \( \sigma(p, T_X) = (e[\overline{U}_1], \forall X.T^\prime_X) \)

Now, by qualification #3, from our \( \vdash^P \) derivation of applicand \( t \) we have that \( T^\prime_X = \forall X.S \rightarrow T \) for some \( S \) and \( T \). The use of the same bound type variables \( X \) as used in \( \forall X.T^\prime_X \) is justified by rewriting the equality concerning \( \sigma T^\prime_X \) above with this new information:

\[ \sigma(p, \forall X.S \rightarrow T = (e''[\overline{U}_1], \forall X.T^\prime_X) \]

We now appeal to completeness of \( \vdash \) wrt \( \vdash \). We satisfy its preconditions:

• \( \Gamma \vdash e''[\overline{U}_1][\overline{U}_2] : S^\prime \rightarrow T^\prime \) and \( \Gamma \vdash t' : S^\prime \rightsquigarrow e' \)

The second of these we get by mutual induction on the completeness of \( \vdash \) wrt \( \vdash \), noting that \( e' \) occurs in a non-applicand position.

• some \( \sigma'' \) with \( \text{dom}(\sigma'') = MV(\Gamma, p[\overline{X}]) \)

where \( \sigma''(p[\overline{X}], S \rightarrow T) = ((e''[\overline{U}_1], [\overline{U}_2], S \rightarrow T^\prime) \)

and \( (|\emptyset|,|\overline{X}|) = (|\emptyset|,[\overline{U}_2]) \)

Note that we parenthesize \((e''[\overline{U}_1])\) for clarification. We are not providing vectorized type arguments \( \overline{U}_1 \) and \( \overline{U}_2 \) to the theorem – we are providing type arguments \( \emptyset \) and \( \overline{U}_2 \), and corresponding \( \emptyset \) and \( \overline{X} \) for the vectorized type meta-variables.

The \( \sigma'' \) we provide is \( [\overline{U}_2/\overline{X}] \circ \sigma \)

Having set this up, we get the following from mutual induction:

• \( \Gamma \vdash (p: \forall X. S \rightarrow T, \sigma_{id}) \).

• some \( \sigma' \) with \( \text{dom}(\sigma') = MV(\Gamma, p') \)

where \( \sigma'(p', T'') = ((e''[\overline{U}_1], [\overline{U}_2], e', T') \)

which is what we need to conclude.

\[ ^5 \text{or at least some attempt at it} \]
5.4 Qualified Completeness of $\vdash \text{wrt } \vdash$

**Theorem 13.** Under the qualifications of Definition 7, if

- $\Gamma \vdash e \mid \{U_1, U_2\} : S' \to T'$ and $\Gamma \vdash \tau' : S' \rightsquigarrow e'$
- and some $\sigma$ with $\text{dom}(\sigma) = MV(\Gamma, p \mid \{X_1, X_2\})$
  where $(p \mid \{X_1, X_2\}, S \to T) = (e \mid \{U_1, U_2\}, S' \to T')$
  (and $(\mid \{X_1, X_2\} = (\mid \{U_1, U_2\}$)

then

- $\Gamma \vdash (p \mid \{X_1\} : \forall X_2. S \to T, \sigma_{id}) \cdot \tau' : T'' \rightsquigarrow (p', \sigma_{id})$
- with some $\sigma'$ with $\text{dom}(\sigma') = MV(\Gamma, p')$ and where $\sigma (p', T'') = (e \mid \{U_1, U_2\} e', T')$

**Proof.** By induction on $\Gamma$

**Case $\{X_2\} = X, X_2$** We have

- $\Gamma \vdash e \mid \{U_1, U_2\} : S' \to T'$
- $\sigma (p \mid \{X_1\} \mid X_2, S \to T) = (e \mid \{U_1, U_2\}, S' \to T')$

We appeal to the IH using variable groups $X_2^1 = X_1, X$ and $X_2$, noting that this regrouping does not keep us from providing the conditions we received on our assumed derivation to the inductive invocation. We get

- $\Gamma \vdash (p \mid \{X_1\} : \forall X_2. S \to T, \sigma_{id}) \cdot \tau' : T'' \rightsquigarrow (p', \sigma_{id})$
- with some $\sigma'$ with $\text{dom}(\sigma') = MV(\Gamma, p')$ and where $\sigma (p', T'') = (e \mid \{U_1, U_2\} e', T')$

From this we derive

$$\frac{\Gamma \vdash (p \mid \{X_1\} : \forall X_2. S \to T, \sigma_{id}) \cdot \tau' : T'' \rightsquigarrow (p', \sigma_{id})}{\Gamma \vdash (p \mid \{X_1\} : \forall X, X_2. S \to T, \sigma_{id}) \cdot \tau' : T'' \rightsquigarrow (p', \sigma_{id})} \text{ PF}$$

And provide the $\sigma'$ prime we received from our IH, noting that the conditions on it are precisely what we need to conclude.

**Case $\{X_2\} = \emptyset$** We have

- $\Gamma \vdash e \mid \{U_1\} : S' \to T'$
- $\Gamma \vdash \tau' : S' \rightsquigarrow e'$
- and $\sigma (p \mid \{X_1\}, S \to T) = (e \mid \{U_1\}, S' \to T')$.

To proceed, we must do case analysis on whether $MV(\Gamma, S) = \emptyset$ or not.

**Subcase $MV(\Gamma, S) = \emptyset$:** Because $MV(\Gamma, S) \subseteq MV(\Gamma, p) = \text{dom}(\sigma)$, we have $\sigma S = (\sigma \cap MV(\Gamma, S))(S) = \sigma_{id}(S) = S'$.

So we have by rewriting our second assumption that

$$\Gamma \vdash \tau' : S \rightsquigarrow e'$$

By using the fact that checking mode extends synthesizing for the specificational rules (Lemma 20) we can derive $\Gamma \vdash \tau' : S \rightsquigarrow e'$

to get

$$\frac{MV(\Gamma, S) = \emptyset \quad \Gamma \vdash \tau' : S \rightsquigarrow e'}{\Gamma \vdash (p \mid \{X_1\} : S \to T, \sigma_{id}) \cdot \tau' : T \rightsquigarrow (p \mid \{X_1\} e', \sigma_{id})} \text{ PChk}$$

We must now provide a suitable $\sigma'$ completing our partial type synthesis. Pick our assumed $\sigma$. Then we have

- $\text{dom}(\sigma) = MV(\Gamma, p \mid \{X_1\} e')$
- $\sigma (p \mid \{X_1\} e', T) = (e \mid \{U_1\} e', T')$

allowing us to conclude this sub-case.
Subcase $MV(\Gamma, S) = \overline{Y} \neq \emptyset$: We know that $MV(\Gamma, S) = \overline{Y} \subseteq MV(\Gamma, p) = dom(\sigma)$. Let $\sigma_{\Gamma} = \sigma \cap \overline{Y}$. Then we know $\sigma S = \sigma_{\Gamma}(S) = S'$. We have

$\Gamma \vdash \overline{\varphi} \; t' : \sigma_{\Gamma} S \rightsquigarrow e'$

We can derive

$$
\begin{array}{c}
\frac{MV(\Gamma, S) = \overline{Y} \neq \emptyset \quad \Gamma \vdash \overline{\varphi} \; t' : \sigma_{\Gamma} S \rightsquigarrow e}{\Gamma \vdash (p[\overline{X_1}] : S \rightarrow T, \sigma_{id}) \cdot t' : \sigma_{\Gamma} T \rightsquigarrow ((\sigma_{\Gamma} p[\overline{X_1}]) e', \sigma_{id})} 
\end{array} \text{ PSyn}
$$

We must now pick a suitable $\sigma'$. Pick $\sigma - \sigma_{\Gamma}$. We have

- $\text{dom}(\sigma - \sigma_{\Gamma}) = MV(\Gamma, p[\overline{X_1}] e') - \overline{Y} = MV(\Gamma, (\sigma_{\Gamma} p[\overline{X_1}]) e')$

- $\sigma' \sigma_{\Gamma} (p[\overline{X_1}] e', \sigma_{\Gamma} T) = \sigma (p[\overline{X_1}] e', T) = (e[\overline{U_1}] e', T')$

which is what we need to conclude.

\[\square\]

5.5 Lemma: Checking extends Synthesizing (Specification)

**Lemma 20.** If $\Gamma \vdash \overline{\varphi} \; t : T \rightsquigarrow e$ then $\Gamma \vdash \overline{\varphi} \; t : T \Rightarrow e$

**Proof.** Directly. Take the assumed derivation of $\vdash \overline{\varphi}$, invoke completeness of $\vdash \overline{\varphi}$ wrt $\vdash \overline{\varphi}$ (refthmcomplete-alg), use the fact that checking extends synthesizing for the algorithmic rules (Lemma 16), and then finish by invoking soundness of the $\vdash \overline{\varphi}$ wrt $\vdash \overline{\varphi}$ (Theorem 1). \[\square\]