

Verified Metatheory and Type Inference for a Name-Carrying Simply-Typed λ -Calculus

Michael Rawson

May 26, 2024

Abstract

I formalise a Church-style simply-typed λ -calculus, extended with pairs, a unit value, and projection functions, and show some metatheory of the calculus, such as the subject reduction property. Particular attention is paid to the treatment of names in the calculus. A nominal style of binding is used, but I use a manual approach over Nominal Isabelle in order to extract an executable type inference algorithm. More information can be found in my [undergraduate dissertation](#).

Contents

```
theory Fresh
imports Main
begin
```

```
class fresh =
  fixes fresh-in :: 'a set  $\Rightarrow$  'a
  assumes finite S  $\Longrightarrow$  fresh-in S  $\notin$  S
```

```
instantiation nat :: fresh
```

```
begin
```

```
definition fresh-in-nat :: nat set  $\Rightarrow$  nat where
```

```
[code]: fresh-in-nat S  $\equiv$  (if Set.is-empty S then 0 else Max S + 1)
```

```
instance proof
```

```
fix S :: nat set
```

```
assume finite S
```

```
consider Set.is-empty S |  $\neg$ Set.is-empty S by auto
```

```
thus fresh-in S  $\notin$  S unfolding fresh-in-nat-def
```

```
proof(cases)
```

```
case 1
```

```
hence S = {} using Set.is-empty-def by metis
```

```
hence 0  $\notin$  S by auto
```

```
thus (if Set.is-empty S then 0 else Max S + 1)  $\notin$  S using 1 by auto
```

```
next
```

```

    case 2
    have  $Max\ S + 1 \notin S$ 
    using ⟨finite S⟩ Max.coboundedI add-le-same-cancel1 not-one-le-zero
    by blast
    thus (if Set.is-empty S then 0 else  $Max\ S + 1$ )  $\notin S$  using 2 by auto
  next
qed
qed
end

end
theory Permutation
imports Main
begin

type-synonym 'a swp = 'a × 'a
type-synonym 'a preprm = 'a swp list

definition preprm-id :: 'a preprm where preprm-id = []

fun swp-apply :: 'a swp ⇒ 'a ⇒ 'a where
  swp-apply (a, b) x = (if x = a then b else (if x = b then a else x))

fun preprm-apply :: 'a preprm ⇒ 'a ⇒ 'a where
  preprm-apply [] x = x
| preprm-apply (s # ss) x = swp-apply s (preprm-apply ss x)

definition preprm-compose :: 'a preprm ⇒ 'a preprm ⇒ 'a preprm where
  preprm-compose f g ≡ f @ g

definition preprm-unit :: 'a ⇒ 'a ⇒ 'a preprm where
  preprm-unit a b ≡ [(a, b)]

definition preprm-ext :: 'a preprm ⇒ 'a preprm ⇒ bool (infix =p 100) where
  π =p σ ≡ ∀ x. preprm-apply π x = preprm-apply σ x

definition preprm-inv :: 'a preprm ⇒ 'a preprm where
  preprm-inv π ≡ rev π

lemma swp-apply-unequal:
  assumes  $x \neq y$ 
  shows  $swp-apply\ s\ x \neq swp-apply\ s\ y$ 
proof (cases s)
  case (Pair a b)
  consider  $x = a \mid x = b \mid x \neq a \wedge x \neq b$  by auto
  thus ?thesis proof (cases)
    case 1
    have  $swp-apply\ s\ x = b$  using ⟨s = (a, b)⟩ ⟨x = a⟩ by simp
    moreover have  $swp-apply\ s\ y \neq b$  using ⟨s = (a, b)⟩ ⟨x = a⟩ ⟨x ≠ y⟩

```

```

    by(cases y = b, simp-all)
  ultimately show ?thesis by metis
next
case 2
  have swp-apply s x = a using ⟨s = (a, b)⟩ ⟨x = b⟩ by simp
  moreover have swp-apply s y ≠ a using ⟨s = (a, b)⟩ ⟨x = b⟩ ⟨x ≠ y⟩
    by(cases y = a, simp-all)
  ultimately show ?thesis by metis
next
case 3
  have swp-apply s x = x using ⟨s = (a, b)⟩ ⟨x ≠ a ∧ x ≠ b⟩ by simp
  consider y = a | y = b | y ≠ a ∧ y ≠ b by auto
  hence swp-apply s y ≠ x proof(cases)
    case 1
      hence swp-apply s y = b using ⟨s = (a, b)⟩ by simp
      thus ?thesis using ⟨x ≠ a ∧ x ≠ b⟩ by metis
    next
    case 2
      hence swp-apply s y = a using ⟨s = (a, b)⟩ by simp
      thus ?thesis using ⟨x ≠ a ∧ x ≠ b⟩ by metis
    next
    case 3
      hence swp-apply s y = y using ⟨s = (a, b)⟩ by simp
      thus ?thesis using ⟨x ≠ y⟩ by metis
  next
  qed
  thus ?thesis using ⟨swp-apply s x = x⟩ ⟨x ≠ y⟩ by metis
next
qed
next
qed

```

lemma *preprm-ext-reflexive*:
 shows $x =_p x$
 unfolding *preprm-ext-def* by auto

corollary *preprm-ext-reflp*:
 shows *reflp preprm-ext*
 unfolding *reflp-def* using *preprm-ext-reflexive* by auto

lemma *preprm-ext-symmetric*:
 assumes $x =_p y$
 shows $y =_p x$
 using *assms* unfolding *preprm-ext-def* by auto

corollary *preprm-ext-symp*:
 shows *symp preprm-ext*
 unfolding *symp-def* using *preprm-ext-symmetric* by auto

lemma *preprm-ext-transitive*:
 assumes $x =_p y$ and $y =_p z$
 shows $x =_p z$
using *assms unfolding preprm-ext-def* **by** *auto*

corollary *preprm-ext-transp*:
 shows *transp preprm-ext*
unfolding *transp-def* **using** *preprm-ext-transitive* **by** *auto*

lemma *preprm-apply-composition*:
 shows *preprm-apply (preprm-compose f g) x = preprm-apply f (preprm-apply g x)*
unfolding *preprm-compose-def*
by(*induction f, simp-all*)

lemma *preprm-apply-unequal*:
 assumes $x \neq y$
 shows *preprm-apply π x \neq preprm-apply π y*
using *assms proof(induction π , simp)*
case (*Cons s ss*)
 have *preprm-apply (s # ss) x = swp-apply s (preprm-apply ss x)*
 and *preprm-apply (s # ss) y = swp-apply s (preprm-apply ss y)* **by** *auto*
 thus *?case using Cons.IH $\langle x \neq y \rangle$ swp-apply-unequal* **by** *metis*
next
qed

lemma *preprm-unit-equal-id*:
 shows *preprm-unit a a =_p preprm-id*
unfolding *preprm-ext-def preprm-unit-def preprm-id-def*
by *simp*

lemma *preprm-unit-inaction*:
 assumes $x \neq a$ and $x \neq b$
 shows *preprm-apply (preprm-unit a b) x = x*
unfolding *preprm-unit-def* **using** *assms* **by** *simp*

lemma *preprm-unit-action*:
 shows *preprm-apply (preprm-unit a b) a = b*
unfolding *preprm-unit-def* **by** *simp*

lemma *preprm-unit-commutes*:
 shows *preprm-unit a b =_p preprm-unit b a*
unfolding *preprm-ext-def preprm-unit-def*
by *simp*

lemma *preprm-singleton-involution*:
 shows *preprm-compose [s] [s] =_p preprm-id*
unfolding *preprm-ext-def preprm-compose-def preprm-unit-def preprm-id-def*
proof –

obtain $s1\ s2$ **where** $s1 = fst\ s\ s2 = snd\ s$ **by** *auto*
hence $s = (s1, s2)$ **by** *simp*
thus $\forall x. preprm-apply\ ([s]\ @\ [s])\ x = preprm-apply\ []\ x$
by *simp*
qed

lemma *preprm-unit-involution*:
shows $preprm-compose\ (preprm-unit\ a\ b)\ (preprm-unit\ a\ b) =_p\ preprm-id$
unfolding *preprm-unit-def*
using *preprm-singleton-involution*.

lemma *preprm-apply-id*:
shows $preprm-apply\ preprm-id\ x = x$
unfolding *preprm-id-def*
by *simp*

lemma *preprm-apply-injective*:
shows $inj\ (preprm-apply\ \pi)$
unfolding *inj-on-def* **proof**(*rule+*)
fix $x\ y$
assume $preprm-apply\ \pi\ x = preprm-apply\ \pi\ y$
thus $x = y$ **proof**(*induction* π)
case *Nil*
thus *?case* **by** *auto*
next
case (*Cons* $s\ ss$)
hence $swp-apply\ s\ (preprm-apply\ ss\ x) = swp-apply\ s\ (preprm-apply\ ss\ y)$ **by**
auto
thus *?case* **using** *swp-apply-unequal* *Cons.IH* **by** *metis*
next
qed
qed

lemma *preprm-disagreement-composition*:
assumes $a \neq b\ b \neq c\ a \neq c$
shows $\{x. preprm-apply\ (preprm-compose\ (preprm-unit\ a\ b)\ (preprm-unit\ b\ c))\ x \neq preprm-apply\ (preprm-unit\ a\ c)\ x\} = \{a, b\}$
unfolding *preprm-unit-def* *preprm-compose-def* **proof**
show $\{x. preprm-apply\ ([a, b])\ @\ [(b, c)]\ x \neq preprm-apply\ [(a, c)]\ x\} \subseteq \{a, b\}$
proof
fix x
have $x \notin \{a, b\} \implies x \notin \{x. preprm-apply\ ([a, b])\ @\ [(b, c)]\ x \neq preprm-apply\ [(a, c)]\ x\}$
proof –
assume $x \notin \{a, b\}$
hence $x \neq a \wedge x \neq b$ **by** *auto*

hence $\text{preprm-apply } [(a, b)] @ [(b, c)] x = \text{preprm-apply } [(a, c)] x$ **by** *simp*
thus $x \notin \{x. \text{preprm-apply } [(a, b)] @ [(b, c)] x \neq \text{preprm-apply } [(a, c)] x\}$
by *auto*
qed
thus $x \in \{x. \text{preprm-apply } [(a, b)] @ [(b, c)] x \neq \text{preprm-apply } [(a, c)] x\}$
 $\implies x \in \{a, b\}$
by *blast*
qed
show $\{a, b\} \subseteq \{x. \text{preprm-apply } [(a, b)] @ [(b, c)] x \neq \text{preprm-apply } [(a, c)] x\}$
proof
fix x
assume $x \in \{a, b\}$
from *this* **consider** $x = a \mid x = b$ **by** *auto*
thus $x \in \{x. \text{preprm-apply } [(a, b)] @ [(b, c)] x \neq \text{preprm-apply } [(a, c)] x\}$
using *assms* **by** (*cases, simp-all*)
qed
qed

lemma *preprm-compose-push*:

shows

$\text{preprm-compose } \pi (\text{preprm-unit } a \ b) = p$

$\text{preprm-compose } (\text{preprm-unit } (\text{preprm-apply } \pi \ a) (\text{preprm-apply } \pi \ b)) \ \pi$

unfolding *preprm-ext-def preprm-unit-def*

by (*simp add: inj-eq preprm-apply-composition preprm-apply-injective*)

lemma *preprm-ext-compose-left*:

assumes $P =_p \ S$

shows $\text{preprm-compose } \pi \ P =_p \ \text{preprm-compose } \pi \ S$

using *assms* **unfolding** *preprm-ext-def*

using *preprm-apply-composition* **by** *metis*

lemma *preprm-ext-compose-right*:

assumes $P =_p \ S$

shows $\text{preprm-compose } P \ \pi =_p \ \text{preprm-compose } S \ \pi$

using *assms* **unfolding** *preprm-ext-def*

using *preprm-apply-composition* **by** *metis*

lemma *preprm-ext-uncompose*:

assumes $\pi =_p \ \sigma \ \text{preprm-compose } \pi \ P =_p \ \text{preprm-compose } \sigma \ S$

shows $P =_p \ S$

using *assms* **unfolding** *preprm-ext-def*

proof –

assume $*$: $\forall x. \text{preprm-apply } \pi \ x = \text{preprm-apply } \sigma \ x$

assume $\forall x. \text{preprm-apply } (\text{preprm-compose } \pi \ P) \ x = \text{preprm-apply } (\text{preprm-compose } \sigma \ S) \ x$

hence $\forall x. \text{preprm-apply } \pi \ (\text{preprm-apply } P \ x) = \text{preprm-apply } \sigma \ (\text{preprm-apply } S \ x)$

$S x$)
using *preprm-apply-composition* **by** *metis*
hence $\forall x. \text{preprm-apply } \pi (\text{preprm-apply } P x) = \text{preprm-apply } \pi (\text{preprm-apply } S x)$
 $S x$)
using $*$ **by** *metis*
thus $\forall x. \text{preprm-apply } P x = \text{preprm-apply } S x$
using *preprm-apply-injective* **unfolding** *inj-on-def* **by** *fastforce*
qed

lemma *preprm-inv-compose*:
shows $\text{preprm-compose } (\text{preprm-inv } \pi) \pi =_p \text{preprm-id}$
unfolding *preprm-inv-def*
proof(*induction* π , *simp* *add*: *preprm-ext-def* *preprm-id-def* *preprm-compose-def*)
case (*Cons* p ps)
hence *IH*: $(\text{preprm-compose } (\text{rev } ps) ps) =_p \text{preprm-id}$ **by** *auto*

have $(\text{preprm-compose } (\text{rev } (p \# ps)) (p \# ps)) =_p (\text{preprm-compose } (\text{rev } ps)$
 $(\text{preprm-compose } (\text{preprm-compose } [p] [p]) ps))$
unfolding *preprm-compose-def* **using** *preprm-ext-reflexive* **by** *simp*
moreover **have** $\dots =_p (\text{preprm-compose } (\text{rev } ps) (\text{preprm-compose } \text{preprm-id}$
 $ps))$
using *preprm-singleton-involution* *preprm-ext-compose-left* *preprm-ext-compose-right*
by *metis*
moreover **have** $\dots =_p (\text{preprm-compose } (\text{rev } ps) ps)$
unfolding *preprm-compose-def* *preprm-id-def* **using** *preprm-ext-reflexive* **by**
simp
moreover **have** $\dots =_p \text{preprm-id}$ **using** *IH*.
ultimately show *?case* **using** *preprm-ext-transitive* **by** *metis*
next
qed

lemma *preprm-inv-involution*:
shows $\text{preprm-inv } (\text{preprm-inv } \pi) = \pi$
unfolding *preprm-inv-def* **by** *simp*

lemma *preprm-inv-ext*:
assumes $\pi =_p \sigma$
shows $\text{preprm-inv } \pi =_p \text{preprm-inv } \sigma$
proof –
have
 $(\text{preprm-compose } (\text{preprm-inv } (\text{preprm-inv } \pi)) (\text{preprm-inv } \pi)) =_p \text{preprm-id}$
 $(\text{preprm-compose } (\text{preprm-inv } (\text{preprm-inv } \sigma)) (\text{preprm-inv } \sigma)) =_p \text{preprm-id}$
using *preprm-inv-compose* **by** *metis+*
hence
 $(\text{preprm-compose } \pi (\text{preprm-inv } \pi)) =_p \text{preprm-id}$
 $(\text{preprm-compose } \sigma (\text{preprm-inv } \sigma)) =_p \text{preprm-id}$
using *preprm-inv-involution* **by** *metis+*
hence $(\text{preprm-compose } \pi (\text{preprm-inv } \pi)) =_p (\text{preprm-compose } \sigma (\text{preprm-inv } \sigma))$
 $\sigma))$

using *preprm-ext-transitive preprm-ext-symmetric* **by** *metis*
thus *preprm-inv $\pi = p$ preprm-inv σ*
using *preprm-ext-uncompose assms* **by** *metis*
qed

quotient-type *'a prm = 'a preprm / preprm-ext*
proof(*rule equivpI*)
show *reflp preprm-ext* **using** *preprm-ext-reflp*.
show *symp preprm-ext* **using** *preprm-ext-symp*.
show *transp preprm-ext* **using** *preprm-ext-transp*.
qed

lift-definition *prm-id :: 'a prm (ε) is preprm-id.*

lift-definition *prm-apply :: 'a prm \Rightarrow 'a \Rightarrow 'a (infix \$ 140) is preprm-apply*
unfolding *preprm-ext-def*
using *preprm-apply.simps* **by** *auto*

lift-definition *prm-compose :: 'a prm \Rightarrow 'a prm \Rightarrow 'a prm (infixr \diamond 145) is*
preprm-compose
unfolding *preprm-ext-def*
by(*simp only: preprm-apply-composition, simp*)

lift-definition *prm-unit :: 'a \Rightarrow 'a \Rightarrow 'a prm ($[- \leftrightarrow -]$) is preprm-unit.*

lift-definition *prm-inv :: 'a prm \Rightarrow 'a prm is preprm-inv*
using *preprm-inv-ext*.

lemma *prm-apply-composition:*
fixes *f g :: 'a prm and x :: 'a*
shows *f \diamond g \$ x = f \$ (g \$ x)*
by(*transfer, metis preprm-apply-composition*)

lemma *prm-apply-unequal:*
fixes *$\pi :: 'a prm$ and $x y :: 'a$*
assumes *$x \neq y$*
shows *$\pi $ x \neq \pi $ y$*
using *assms* **by** (*transfer, metis preprm-apply-unequal*)

lemma *prm-unit-equal-id:*
fixes *a :: 'a*
shows *$[a \leftrightarrow a] = \varepsilon$*
by (*transfer, metis preprm-unit-equal-id*)

lemma *prm-unit-inaction:*
fixes *a b x :: 'a*
assumes *$x \neq a$ and $x \neq b$*
shows *$[a \leftrightarrow b] $ x = x$*
using *assms*

by (transfer, metis preprm-unit-inaction)

lemma *prm-unit-action*:

fixes $a b :: 'a$

shows $[a \leftrightarrow b] \$ a = b$

by (transfer, metis preprm-unit-action)

lemma *prm-unit-commutes*:

fixes $a b :: 'a$

shows $[a \leftrightarrow b] = [b \leftrightarrow a]$

by (transfer, metis preprm-unit-commutes)

lemma *prm-unit-involution*:

fixes $a b :: 'a$

shows $[a \leftrightarrow b] \diamond [a \leftrightarrow b] = \varepsilon$

by (transfer, metis preprm-unit-involution)

lemma *prm-apply-id*:

fixes $x :: 'a$

shows $\varepsilon \$ x = x$

by (transfer, metis preprm-apply-id)

lemma *prm-apply-injective*:

shows inj (prm-apply π)

by (transfer, metis preprm-apply-injective)

lemma *prm-inv-compose*:

shows (prm-inv π) $\diamond \pi = \varepsilon$

by (transfer, metis preprm-inv-compose)

interpretation $'a$ prm: semigroup prm-compose

unfolding semigroup-def by (transfer, simp add: preprm-compose-def preprm-ext-def)

interpretation $'a$ prm: group prm-compose prm-id prm-inv

unfolding group-def group-axioms-def

proof –

have semigroup (\diamond) using $'a$ prm.semigroup-axioms.

moreover have $\forall a. \varepsilon \diamond a = a$ by (transfer, simp add: preprm-id-def preprm-compose-def preprm-ext-def)

moreover have $\forall a. \text{prm-inv } a \diamond a = \varepsilon$ using prm-inv-compose by blast

ultimately show semigroup (\diamond) $\wedge (\forall a. \varepsilon \diamond a = a) \wedge (\forall a. \text{prm-inv } a \diamond a = \varepsilon)$

by blast

qed

definition *prm-set* :: $'a$ prm $\Rightarrow 'a$ set $\Rightarrow 'a$ set (infix $\{\$\}$ 140) where

$\text{prm-set } \pi S \equiv \text{image } (\text{prm-apply } \pi) S$

lemma *prm-set-apply-compose*:

shows $\pi \{\$\} (\sigma \{\$\} S) = (\pi \diamond \sigma) \{\$\} S$

unfolding *prm-set-def* **proof** –
have $(\$)\ \pi \text{ ' } (\$)\ \sigma \text{ ' } S = (\lambda x. \pi \$ x) \text{ ' } (\lambda x. \sigma \$ x) \text{ ' } S$ **by** *simp*
moreover have $\dots = (\lambda x. \pi \$ (\sigma \$ x)) \text{ ' } S$ **by** *auto*
moreover have $\dots = (\lambda x. (\pi \diamond \sigma) \$ x) \text{ ' } S$ **using** *prm-apply-composition* **by**
metis
moreover have $\dots = (\pi \diamond \sigma) \{ \$ \} S$ **using** *prm-set-def* **by** *metis*
ultimately show $(\$)\ \pi \text{ ' } (\$)\ \sigma \text{ ' } S = (\$)\ (\pi \diamond \sigma) \text{ ' } S$ **by** *metis*
qed

lemma *prm-set-membership*:
assumes $x \in S$
shows $\pi \$ x \in \pi \{ \$ \} S$
using *assms* **unfolding** *prm-set-def* **by** *simp*

lemma *prm-set-notmembership*:
assumes $x \notin S$
shows $\pi \$ x \notin \pi \{ \$ \} S$
using *assms* **unfolding** *prm-set-def*
by (*simp add: inj-image-mem-iff prm-apply-injective*)

lemma *prm-set-singleton*:
shows $\pi \{ \$ \} \{ x \} = \{ \pi \$ x \}$
unfolding *prm-set-def* **by** *auto*

lemma *prm-set-id*:
shows $\varepsilon \{ \$ \} S = S$
unfolding *prm-set-def*
proof –
have $(\$)\ \varepsilon \text{ ' } S = (\lambda x. \varepsilon \$ x) \text{ ' } S$ **by** *simp*
moreover have $\dots = (\lambda x. x) \text{ ' } S$ **using** *prm-apply-id* **by** *metis*
moreover have $\dots = S$ **by** *auto*
ultimately show $(\$)\ \varepsilon \text{ ' } S = S$ **by** *metis*
qed

lemma *prm-set-unit-inaction*:
assumes $a \notin S$ **and** $b \notin S$
shows $[a \leftrightarrow b] \{ \$ \} S = S$
proof
show $[a \leftrightarrow b] \{ \$ \} S \subseteq S$ **proof**
fix x
assume $H: x \in [a \leftrightarrow b] \{ \$ \} S$
from this obtain y **where** $x = [a \leftrightarrow b] \$ y$ **unfolding** *prm-set-def* **using**
imageE **by** *metis*
hence $y \in S$ **using** H *inj-image-mem-iff* *prm-apply-injective* *prm-set-def* **by**
metis
hence $y \neq a$ **and** $y \neq b$ **using** *assms* **by** *auto*
hence $x = y$ **using** *prm-unit-inaction* $\langle x = [a \leftrightarrow b] \$ y \rangle$ **by** *metis*
thus $x \in S$ **using** $\langle y \in S \rangle$ **by** *auto*
qed

show $S \subseteq [a \leftrightarrow b] \{\$\} S$ **proof**
fix x
assume $H: x \in S$
hence $x \neq a$ **and** $x \neq b$ **using** *assms* **by** *auto*
hence $x = [a \leftrightarrow b] \$ x$ **using** *prm-unit-inaction* **by** *metis*
thus $x \in [a \leftrightarrow b] \{\$\} S$ **unfolding** *prm-set-def* **using** H **by** *simp*
qed
qed

lemma *prm-set-unit-action*:
assumes $a \in S$ **and** $b \notin S$
shows $[a \leftrightarrow b] \{\$\} S = S - \{a\} \cup \{b\}$
proof
show $[a \leftrightarrow b] \{\$\} S \subseteq S - \{a\} \cup \{b\}$ **proof**
fix x
assume $H: x \in [a \leftrightarrow b] \{\$\} S$
from *this* **obtain** y **where** $x = [a \leftrightarrow b] \$ y$ **unfolding** *prm-set-def* **using** *imageE* **by** *metis*
hence $y \in S$ **using** H *inj-image-mem-iff* *prm-apply-injective* *prm-set-def* **by** *metis*
hence $y \neq b$ **using** *assms* **by** *auto*
consider $y = a \mid y \neq a$ **by** *auto*
thus $x \in S - \{a\} \cup \{b\}$ **proof**(*cases*)
case 1
hence $x = b$ **using** $\langle x = [a \leftrightarrow b] \$ y \rangle$ **using** *prm-unit-action* **by** *metis*
thus *?thesis* **by** *auto*
next
case 2
hence $x = y$ **using** $\langle x = [a \leftrightarrow b] \$ y \rangle$ **using** *prm-unit-inaction* $\langle y \neq b \rangle$ **by** *metis*
hence $x \in S$ **and** $x \neq a$ **using** $\langle y \in S \rangle$ $\langle y \neq a \rangle$ **by** *auto*
thus *?thesis* **by** *auto*
next
qed
qed

show $S - \{a\} \cup \{b\} \subseteq [a \leftrightarrow b] \{\$\} S$ **proof**
fix x
assume $H: x \in S - \{a\} \cup \{b\}$
hence $x \neq a$ **using** *assms* **by** *auto*
consider $x = b \mid x \neq b$ **by** *auto*
thus $x \in [a \leftrightarrow b] \{\$\} S$ **proof**(*cases*)
case 1
hence $x = [a \leftrightarrow b] \$ a$ **using** *prm-unit-action* **by** *metis*
thus *?thesis* **using** $\langle a \in S \rangle$ *prm-set-membership* **by** *metis*
next
case 2
hence $x \in S$ **using** H **by** *auto*
moreover **have** $x = [a \leftrightarrow b] \$ x$ **using** *prm-unit-inaction* $\langle x \neq a \rangle$ $\langle x \neq b \rangle$
by *metis*

```

      ultimately show ?thesis using prm-set-membership by metis
    next
    qed
  qed
qed

lemma prm-set-distributes-union:
  shows  $\pi \{ \$ \} (S \cup T) = (\pi \{ \$ \} S) \cup (\pi \{ \$ \} T)$ 
unfolding prm-set-def by auto

lemma prm-set-distributes-difference:
  shows  $\pi \{ \$ \} (S - T) = (\pi \{ \$ \} S) - (\pi \{ \$ \} T)$ 
unfolding prm-set-def using prm-apply-injective image-set-diff by metis

definition prm-disagreement :: 'a prm  $\Rightarrow$  'a prm  $\Rightarrow$  'a set (ds) where
  prm-disagreement  $\pi \sigma \equiv \{x. \pi \$ x \neq \sigma \$ x\}$ 

lemma prm-disagreement-ext:
  shows  $x \in ds \pi \sigma \equiv \pi \$ x \neq \sigma \$ x$ 
unfolding prm-disagreement-def by simp

lemma prm-disagreement-composition:
  assumes  $a \neq b \ b \neq c \ a \neq c$ 
  shows  $ds ([a \leftrightarrow b] \diamond [b \leftrightarrow c]) [a \leftrightarrow c] = \{a, b\}$ 
using assms unfolding prm-disagreement-def by (transfer, metis preprm-disagreement-composition)

lemma prm-compose-push:
  shows  $\pi \diamond [a \leftrightarrow b] = [\pi \$ a \leftrightarrow \pi \$ b] \diamond \pi$ 
by (transfer, metis preprm-compose-push)

end
theory PreSimplyTyped
imports Fresh Permutation
begin

type-synonym tvar = nat

datatype type =
  TUnit
| TVar tvar
| TArr type type
| TPair type type

datatype 'a ptrm =
  PUnit
| PVar 'a
| PApp 'a ptrm 'a ptrm
| PFn 'a type 'a ptrm
| PPair 'a ptrm 'a ptrm

```

| *PFst* 'a *ptrm*
| *PSnd* 'a *ptrm*

fun *ptrm-fvs* :: 'a *ptrm* \Rightarrow 'a *set* **where**
 | *ptrm-fvs* *PUnit* = {}
 | *ptrm-fvs* (*PVar* *x*) = {*x*}
 | *ptrm-fvs* (*PApp* *A B*) = *ptrm-fvs* *A* \cup *ptrm-fvs* *B*
 | *ptrm-fvs* (*PFn* *x* - *A*) = *ptrm-fvs* *A* - {*x*}
 | *ptrm-fvs* (*PPair* *A B*) = *ptrm-fvs* *A* \cup *ptrm-fvs* *B*
 | *ptrm-fvs* (*PFst* *P*) = *ptrm-fvs* *P*
 | *ptrm-fvs* (*PSnd* *P*) = *ptrm-fvs* *P*

fun *ptrm-apply-prm* :: 'a *prm* \Rightarrow 'a *ptrm* \Rightarrow 'a *ptrm* (**infixr** · 150) **where**
 | *ptrm-apply-prm* π *PUnit* = *PUnit*
 | *ptrm-apply-prm* π (*PVar* *x*) = *PVar* (π \$ *x*)
 | *ptrm-apply-prm* π (*PApp* *A B*) = *PApp* (*ptrm-apply-prm* π *A*) (*ptrm-apply-prm* π *B*)
 | *ptrm-apply-prm* π (*PFn* *x* *T* *A*) = *PFn* (π \$ *x*) *T* (*ptrm-apply-prm* π *A*)
 | *ptrm-apply-prm* π (*PPair* *A B*) = *PPair* (*ptrm-apply-prm* π *A*) (*ptrm-apply-prm* π *B*)
 | *ptrm-apply-prm* π (*PFst* *P*) = *PFst* (*ptrm-apply-prm* π *P*)
 | *ptrm-apply-prm* π (*PSnd* *P*) = *PSnd* (*ptrm-apply-prm* π *P*)

inductive *ptrm-alpha-equiv* :: 'a *ptrm* \Rightarrow 'a *ptrm* \Rightarrow *bool* (**infix** \approx 100) **where**
 | *unit*: *PUnit* \approx *PUnit*
 | *var*: (*PVar* *x*) \approx (*PVar* *x*)
 | *app*: [*A* \approx *B*; *C* \approx *D*] \Longrightarrow (*PApp* *A* *C*) \approx (*PApp* *B* *D*)
 | *fn1*: *A* \approx *B* \Longrightarrow (*PFn* *x* *T* *A*) \approx (*PFn* *x* *T* *B*)
 | *fn2*: [*a* \neq *b*; *A* \approx [*a* \leftrightarrow *b*] · *B*; *a* \notin *ptrm-fvs* *B*] \Longrightarrow (*PFn* *a* *T* *A*) \approx (*PFn* *b* *T* *B*)
 | *pair*: [*A* \approx *B*; *C* \approx *D*] \Longrightarrow (*PPair* *A* *C*) \approx (*PPair* *B* *D*)
 | *fst*: *A* \approx *B* \Longrightarrow *PFst* *A* \approx *PFst* *B*
 | *snd*: *A* \approx *B* \Longrightarrow *PSnd* *A* \approx *PSnd* *B*

inductive-cases *unitE*: *PUnit* \approx *Y*
inductive-cases *varE*: *PVar* *x* \approx *Y*
inductive-cases *appE*: *PApp* *A* *B* \approx *Y*
inductive-cases *fnE*: *PFn* *x* *T* *A* \approx *Y*
inductive-cases *pairE*: *PPair* *A* *B* \approx *Y*
inductive-cases *fstE*: *PFst* *P* \approx *Y*
inductive-cases *sndE*: *PSnd* *P* \approx *Y*

lemma *ptrm-prm-apply-id*:
shows $\varepsilon \cdot X = X$
by(*induction* *X*, *simp-all* *add*: *prm-apply-id*)

lemma *ptrm-prm-apply-compose*:
shows $\pi \cdot \sigma \cdot X = (\pi \diamond \sigma) \cdot X$
by(*induction* *X*, *simp-all* *add*: *prm-apply-composition*)

```

lemma ptrm-size-prm:
  shows size X = size (π · X)
  by(induction X, auto)

lemma ptrm-size-alpha-equiv:
  assumes X ≈ Y
  shows size X = size Y
  using assms proof(induction rule: ptrm-alpha-equiv.induct)
    case (fn2 a b A B T)
      hence size A = size B using ptrm-size-prm by metis
      thus ?case by auto
    next
  qed auto

lemma ptrm-fvs-finite:
  shows finite (ptrm-fvs X)
  by(induction X, auto)

lemma ptrm-prm-fvs:
  shows ptrm-fvs (π · X) = π {\$} ptrm-fvs X
  proof(induction X)
    case (PUnit)
      thus ?case unfolding prm-set-def by simp
    next
    case (PVar x)
      have ptrm-fvs (π · PVar x) = ptrm-fvs (PVar (π $ x)) by simp
      moreover have ... = {π $ x} by simp
      moreover have ... = π {\$} {x} using prm-set-singleton by metis
      moreover have ... = π {\$} ptrm-fvs (PVar x) by simp
      ultimately show ?case by metis
    next
    case (PApp A B)
      have ptrm-fvs (π · PApp A B) = ptrm-fvs (PApp (π · A) (π · B)) by simp
      moreover have ... = ptrm-fvs (π · A) ∪ ptrm-fvs (π · B) by simp
      moreover have ... = π {\$} ptrm-fvs A ∪ π {\$} ptrm-fvs B using PApp.IH by
  metis
      moreover have ... = π {\$} (ptrm-fvs A ∪ ptrm-fvs B) using prm-set-distributes-union
  by metis
      moreover have ... = π {\$} ptrm-fvs (PApp A B) by simp
      ultimately show ?case by metis
    next
    case (PFn x T A)
      have ptrm-fvs (π · PFn x T A) = ptrm-fvs (PFn (π $ x) T (π · A)) by simp
      moreover have ... = ptrm-fvs (π · A) - {π $ x} by simp
      moreover have ... = π {\$} ptrm-fvs A - {π $ x} using PFn.IH by metis
      moreover have ... = π {\$} ptrm-fvs A - π {\$} {x} using prm-set-singleton
  by metis
      moreover have ... = π {\$} (ptrm-fvs A - {x}) using prm-set-distributes-difference

```

```

by metis
  moreover have ... =  $\pi \{ \$ \}$  ptrm-fvs (PFn x T A) by simp
  ultimately show ?case by metis
next
case (PPair A B)
  thus ?case
    using prm-set-distributes-union ptrm-apply-prm.simps(5) ptrm-fvs.simps(5)
    by fastforce
next
case (PFst P)
  thus ?case by auto
next
case (PSnd P)
  thus ?case by auto
next
qed

lemma ptrm-alpha-equiv-fvs:
  assumes  $X \approx Y$ 
  shows ptrm-fvs X = ptrm-fvs Y
using assms proof(induction rule: ptrm-alpha-equiv.induct)
  case (fn2 a b A B T)
    have ptrm-fvs (PFn a T A) = ptrm-fvs A - {a} by simp
    moreover have ... = ptrm-fvs ([a  $\leftrightarrow$  b]  $\cdot$  B) - {a} using fn2.IH by metis
    moreover have ... = ([a  $\leftrightarrow$  b] { $ } ptrm-fvs B) - {a} using ptrm-prm-fvs by
metis
    moreover have ... = ptrm-fvs B - {b} proof -
      consider  $b \in \text{ptrm-fvs } B \mid b \notin \text{ptrm-fvs } B$  by auto
      thus ?thesis proof(cases)
        case 1
          have [a  $\leftrightarrow$  b] { $ } ptrm-fvs B - {a} = [b  $\leftrightarrow$  a] { $ } ptrm-fvs B - {a}
using prm-unit-commutes by metis
          moreover have ... = ((ptrm-fvs B - {b})  $\cup$  {a}) - {a}
            using prm-set-unit-action  $\langle b \in \text{ptrm-fvs } B \rangle \langle a \notin \text{ptrm-fvs } B \rangle$  by metis
          moreover have ... = ptrm-fvs B - {b} using  $\langle a \notin \text{ptrm-fvs } B \rangle \langle a \neq b \rangle$ 
            using Diff-insert0 Diff-insert2 Un-insert-right insert-Diff1 insert-is-Un
singletonI
            sup-bot.right-neutral by blast
          ultimately show ?thesis by metis
        next
        case 2
          hence [a  $\leftrightarrow$  b] { $ } ptrm-fvs B - {a} = ptrm-fvs B - {a}
            using prm-set-unit-inaction  $\langle a \notin \text{ptrm-fvs } B \rangle$  by metis
          moreover have ... = ptrm-fvs B using  $\langle a \notin \text{ptrm-fvs } B \rangle$  by simp
          moreover have ... = ptrm-fvs B - {b} using  $\langle b \notin \text{ptrm-fvs } B \rangle$  by simp
          ultimately show ?thesis by metis
      next
    qed
  qed
qed

```

```

    moreover have ... = ptrm-fvs (PFn b T B) by simp
    ultimately show ?case by metis
  next
qed auto

lemma ptrm-alpha-equiv-prm:
  assumes  $X \approx Y$ 
  shows  $\pi \cdot X \approx \pi \cdot Y$ 
using assms proof(induction rule: ptrm-alpha-equiv.induct)
  case (unit)
    thus ?case using ptrm-alpha-equiv.unit by simp
  next
  case (var x)
    thus ?case using ptrm-alpha-equiv.var by simp
  next
  case (app A B C D)
    thus ?case using ptrm-alpha-equiv.app by simp
  next
  case (fn1 A B x T)
    thus ?case using ptrm-alpha-equiv.fn1 by simp
  next
  case (fn2 a b A B T)
    have  $\pi \$ a \neq \pi \$ b$  using  $\langle a \neq b \rangle$  using prm-apply-unequal by metis
    moreover have  $\pi \$ a \notin \text{ptrm-fvs}(\pi \cdot B)$  using  $\langle a \notin \text{ptrm-fvs} B \rangle$ 
    using imageE prm-apply-unequal prm-set-def ptrm-prm-fvs by (metis (no-types,
lifting))
    moreover have  $\pi \cdot A \approx [\pi \$ a \leftrightarrow \pi \$ b] \cdot \pi \cdot B$ 
      using fn2.IH prm-compose-push ptrm-prm-apply-compose by metis
    ultimately show ?case using ptrm-alpha-equiv.fn2 by simp
  next
  case (pair A B C D)
    thus ?case using ptrm-alpha-equiv.pair by simp
  next
  case (fst A B)
    thus ?case using ptrm-alpha-equiv.fst by simp
  next
  case (snd A B)
    thus ?case using ptrm-alpha-equiv.snd by simp
  next
qed

lemma ptrm-swp-transfer:
  shows  $[a \leftrightarrow b] \cdot X \approx Y \iff X \approx [a \leftrightarrow b] \cdot Y$ 
proof -
  have 1:  $[a \leftrightarrow b] \cdot X \approx Y \implies X \approx [a \leftrightarrow b] \cdot Y$ 
proof -
  assume  $[a \leftrightarrow b] \cdot X \approx Y$ 
  hence  $\varepsilon \cdot X \approx [a \leftrightarrow b] \cdot Y$ 
  using ptrm-alpha-equiv-prm ptrm-prm-apply-compose prm-unit-involution by

```

metis
thus *?thesis using ptrm-prm-apply-id by metis*
qed
have 2: $X \approx [a \leftrightarrow b] \cdot Y \implies [a \leftrightarrow b] \cdot X \approx Y$
proof –
assume $X \approx [a \leftrightarrow b] \cdot Y$
hence $[a \leftrightarrow b] \cdot X \approx \varepsilon \cdot Y$
using *ptrm-alpha-equiv-prm ptrm-prm-apply-compose prm-unit-involution by*
metis
thus *?thesis using ptrm-prm-apply-id by metis*
qed
from 1 and 2 **show** $[a \leftrightarrow b] \cdot X \approx Y \iff X \approx [a \leftrightarrow b] \cdot Y$ **by** *blast*
qed

lemma *ptrm-alpha-equiv-fvs-transfer*:
assumes $A \approx [a \leftrightarrow b] \cdot B$ **and** $a \notin \text{ptrm-fvs } B$
shows $b \notin \text{ptrm-fvs } A$
proof –
from $\langle A \approx [a \leftrightarrow b] \cdot B \rangle$ **have** $[a \leftrightarrow b] \cdot A \approx B$ **using** *ptrm-swp-transfer by*
metis
hence $\text{ptrm-fvs } B = [a \leftrightarrow b] \{ \$ \} \text{ptrm-fvs } A$
using *ptrm-alpha-equiv-fvs ptrm-prm-fvs by metis*
hence $a \notin [a \leftrightarrow b] \{ \$ \} \text{ptrm-fvs } A$ **using** $\langle a \notin \text{ptrm-fvs } B \rangle$ **by** *metis*
hence $b \notin [a \leftrightarrow b] \{ \$ \} ([a \leftrightarrow b] \{ \$ \} \text{ptrm-fvs } A)$
using *prn-set-notmembership prm-unit-action by metis*
thus *?thesis using prm-set-apply-compose prm-unit-involution prm-set-id by*
metis
qed

lemma *ptrm-prm-agreement-equiv*:
assumes $\bigwedge a. a \in \text{ds } \pi \sigma \implies a \notin \text{ptrm-fvs } M$
shows $\pi \cdot M \approx \sigma \cdot M$
using *assms proof(induction M arbitrary: $\pi \sigma$)*
case (*PUnit*)
thus *?case using ptrm-alpha-equiv.unit by simp*
next
case (*PVar x*)
consider $x \in \text{ds } \pi \sigma \mid x \notin \text{ds } \pi \sigma$ **by** *auto*
thus *?case proof(cases)*
case 1
hence $x \notin \text{ptrm-fvs } (\text{PVar } x)$ **using** *PVar.premis by blast*
thus *?thesis by simp*
next
case 2
hence $\pi \$ x = \sigma \$ x$ **using** *prn-disagreement-ext by metis*
thus *?thesis using ptrm-alpha-equiv.var by simp*
next
qed
next

```

case (PApp A B)
  hence  $\pi \cdot A \approx \sigma \cdot A$  and  $\pi \cdot B \approx \sigma \cdot B$  by auto
  thus ?case using ptrm-alpha-equiv.app by auto
next
case (PFn x T A)
  consider  $x \notin ds \pi \sigma \mid x \in ds \pi \sigma$  by auto
  thus ?case proof(cases)
    case 1
      hence *:  $\pi \$ x = \sigma \$ x$  using prm-disagreement-ext by metis
      have  $\bigwedge a. a \in ds \pi \sigma \implies a \notin ptrm-fvs A$ 
      proof -
        fix a
        assume  $a \in ds \pi \sigma$ 
        hence  $a \notin ptrm-fvs (PFn x T A)$  using PFn.prem by metis
        hence  $a = x \vee a \notin ptrm-fvs A$  by auto
        thus  $a \notin ptrm-fvs A$  using  $\langle a \in ds \pi \sigma \rangle \langle x \notin ds \pi \sigma \rangle$  by auto
      qed
      thus ?thesis using PFn.IH * ptrm-alpha-equiv.fn1 ptrm-apply-prm.simps(3)
    by fastforce
  next
  case 2
    hence  $\pi \$ x \neq \sigma \$ x$  using prm-disagreement-def CollectD by fastforce
    moreover have  $\pi \$ x \notin ptrm-fvs (\sigma \cdot A)$ 
    proof -
      have  $y \in (ptrm-fvs A) \implies \pi \$ x \neq \sigma \$ y$  for y
      using PFn  $\langle \pi \$ x \neq \sigma \$ x \rangle$  prm-apply-unequal prm-disagreement-ext
      ptrm-fvs.simps(4)
      by (metis Diff-iff empty-iff insert-iff)
      hence  $\pi \$ x \notin \sigma \{ \$ \} ptrm-fvs A$  unfolding prm-set-def by auto
      thus ?thesis using ptrm-prm-fvs by metis
    qed
    moreover have  $\pi \cdot A \approx [\pi \$ x \leftrightarrow \sigma \$ x] \cdot \sigma \cdot A$ 
    proof -
      have  $\bigwedge a. a \in ds \pi ([\pi \$ x \leftrightarrow \sigma \$ x] \diamond \sigma) \implies a \notin ptrm-fvs A$  proof -
        fix a
        assume *:  $a \in ds \pi ([\pi \$ x \leftrightarrow \sigma \$ x] \diamond \sigma)$ 
        hence  $a \neq x$  using  $\langle \pi \$ x \neq \sigma \$ x \rangle$ 
        using prm-apply-composition prm-disagreement-ext prm-unit-action
        ptrm-unit-commutes
        by metis
        hence  $a \in ds \pi \sigma$ 
        using * prm-apply-composition prm-apply-unequal prm-disagreement-ext
        ptrm-unit-inaction
        by metis
        thus  $a \notin ptrm-fvs A$  using  $\langle a \neq x \rangle$  PFn.prem by auto
      qed
      thus ?thesis using PFn by (simp add: ptrm-prm-apply-compose)
    qed
  ultimately show ?thesis using ptrm-alpha-equiv.fn2 by simp

```

```

    next
  qed
next
case (PPair A B)
  hence  $\pi \cdot A \approx \sigma \cdot A$  and  $\pi \cdot B \approx \sigma \cdot B$  by auto
  thus ?case using ptrm-alpha-equiv.pair by auto
next
case (PFst P)
  hence  $\pi \cdot P \approx \sigma \cdot P$  by auto
  thus ?case using ptrm-alpha-equiv.fst by auto
next
case (PSnd P)
  hence  $\pi \cdot P \approx \sigma \cdot P$  by auto
  thus ?case using ptrm-alpha-equiv.snd by auto
next
qed

```

lemma *ptrm-prm-unit-inaction*:

```

  assumes  $a \notin \text{ptrm-fvs } X$   $b \notin \text{ptrm-fvs } X$ 
  shows  $[a \leftrightarrow b] \cdot X \approx X$ 
proof –
  have  $(\bigwedge x. x \in \text{ds } [a \leftrightarrow b] \varepsilon \implies x \notin \text{ptrm-fvs } X)$ 
proof –
  fix  $x$ 
  assume  $x \in \text{ds } [a \leftrightarrow b] \varepsilon$ 
  hence  $[a \leftrightarrow b] \$ x \neq \varepsilon \$ x$ 
    unfolding prm-disagreement-def
    by auto
  hence  $x = a \vee x = b$ 
    using prm-apply-id prm-unit-inaction by metis
  thus  $x \notin \text{ptrm-fvs } X$  using assms by auto
qed
  hence  $[a \leftrightarrow b] \cdot X \approx \varepsilon \cdot X$ 
    using ptrm-prm-agreement-equiv by metis
  thus ?thesis using ptrm-prm-apply-id by metis
qed

```

lemma *ptrm-alpha-equiv-reflexive*:

```

  shows  $M \approx M$ 
by(induction  $M$ , auto simp add: ptrm-alpha-equiv.intros)

```

corollary *ptrm-alpha-equiv-reflp*:

```

  shows reflp ptrm-alpha-equiv
unfolding reflp-def using ptrm-alpha-equiv-reflexive by auto

```

lemma *ptrm-alpha-equiv-symmetric*:

```

  assumes  $X \approx Y$ 
  shows  $Y \approx X$ 
using assms proof(induction rule: ptrm-alpha-equiv.induct, auto simp add: ptrm-alpha-equiv.intros)

```

```

case (fn2 a b A B T)
  have  $b \neq a$  using  $\langle a \neq b \rangle$  by auto
  have  $B \approx [b \leftrightarrow a] \cdot A$  using  $\langle [a \leftrightarrow b] \cdot B \approx A \rangle$ 
    using ptrm-sup-transfer ptrm-unit-commutes by metis

  have  $b \notin \text{ptrm-fvs } A$  using  $\langle a \notin \text{ptrm-fvs } B \rangle \langle A \approx [a \leftrightarrow b] \cdot B \rangle \langle a \neq b \rangle$ 
    using ptrm-alpha-equiv-fvs-transfer by metis

  show ?case using  $\langle b \neq a \rangle \langle B \approx [b \leftrightarrow a] \cdot A \rangle \langle b \notin \text{ptrm-fvs } A \rangle$ 
    using ptrm-alpha-equiv.fn2 by metis
next
qed

corollary ptrm-alpha-equiv-symp:
  shows symp ptrm-alpha-equiv
unfolding symp-def using ptrm-alpha-equiv-symmetric by auto

lemma ptrm-alpha-equiv-transitive:
  assumes  $X \approx Y$  and  $Y \approx Z$ 
  shows  $X \approx Z$ 
using assms proof(induction size X arbitrary: X Y Z rule: less-induct)
  fix X Y Z :: 'a ptrm
  assume IH:  $\bigwedge K Y Z :: 'a \text{ ptrm. size } K < \text{size } X \implies K \approx Y \implies Y \approx Z \implies K \approx Z$ 
  assume  $X \approx Y$  and  $Y \approx Z$ 
  show  $X \approx Z$  proof(cases X)
    case (PUnit)
      hence  $Y = PUnit$  using  $\langle X \approx Y \rangle$  unitE by metis
      hence  $Z = PUnit$  using  $\langle Y \approx Z \rangle$  unitE by metis
      thus ?thesis using ptrm-alpha-equiv.unit  $\langle X = PUnit \rangle$  by metis
    next
    case (PVar x)
      hence  $PVar x \approx Y$  using  $\langle X \approx Y \rangle$  by auto
      hence  $Y = PVar x$  using varE by metis
      hence  $PVar x \approx Z$  using  $\langle Y \approx Z \rangle$  by auto
      hence  $Z = PVar x$  using varE by metis
      thus ?thesis using ptrm-alpha-equiv.var  $\langle X = PVar x \rangle$  by metis
    next
    case (PApp A B)
      obtain C D where  $Y = PApp C D$  and  $A \approx C$  and  $B \approx D$ 
        using appE  $\langle X = PApp A B \rangle \langle X \approx Y \rangle$  by metis
      hence  $PApp C D \approx Z$  using  $\langle Y \approx Z \rangle$  by simp
      from this obtain E F where  $Z = PApp E F$  and  $C \approx E$  and  $D \approx F$  using
        appE by metis

      have  $\text{size } A < \text{size } X$  and  $\text{size } B < \text{size } X$  using  $\langle X = PApp A B \rangle$  by auto
      hence  $A \approx E$  and  $B \approx F$  using IH  $\langle A \approx C \rangle \langle C \approx E \rangle \langle B \approx D \rangle \langle D \approx F \rangle$ 
by auto
      thus ?thesis using  $\langle X = PApp A B \rangle \langle Z = PApp E F \rangle$  ptrm-alpha-equiv.app

```

by *metis*
next
case ($\text{PFn } x \ T \ A$)
from *this* **have** $X: X = \text{PFn } x \ T \ A$.
hence *: $\text{size } A < \text{size } X$ **by** *auto*

obtain $y \ B$ **where** $Y = \text{PFn } y \ T \ B$
and $Y\text{-cases}: (x = y \wedge A \approx B) \vee (x \neq y \wedge A \approx [x \leftrightarrow y]) \cdot B \wedge x \notin \text{ptrm-fvs } B$

B) **using** $\text{fnE } \langle X \approx Y \rangle \langle X = \text{PFn } x \ T \ A \rangle$ **by** *metis*
obtain $z \ C$ **where** $Z: Z = \text{PFn } z \ T \ C$
and $Z\text{-cases}: (y = z \wedge B \approx C) \vee (y \neq z \wedge B \approx [y \leftrightarrow z]) \cdot C \wedge y \notin \text{ptrm-fvs } C$

C) **using** $\text{fnE } \langle Y \approx Z \rangle \langle Y = \text{PFn } y \ T \ B \rangle$ **by** *metis*

consider
 $x = y \ A \approx B$ **and** $y = z \ B \approx C$
 $| x = y \ A \approx B$ **and** $y \neq z \ B \approx [y \leftrightarrow z] \cdot C \ y \notin \text{ptrm-fvs } C$
 $| x \neq y \ A \approx [x \leftrightarrow y] \cdot B \ x \notin \text{ptrm-fvs } B$ **and** $y = z \ B \approx C$
 $| x \neq y \ A \approx [x \leftrightarrow y] \cdot B \ x \notin \text{ptrm-fvs } B$ **and** $y \neq z \ B \approx [y \leftrightarrow z] \cdot C \ y \notin \text{ptrm-fvs } C$ **and** $x = z$
 $| x \neq y \ A \approx [x \leftrightarrow y] \cdot B \ x \notin \text{ptrm-fvs } B$ **and** $y \neq z \ B \approx [y \leftrightarrow z] \cdot C \ y \notin \text{ptrm-fvs } C$ **and** $x \neq z$
using $Y\text{-cases } Z\text{-cases}$ **by** *auto*

thus *?thesis proof(cases)*
case 1
have $A \approx C$ **using** $\langle A \approx B \rangle \langle B \approx C \rangle$ $IH \ *$ **by** *metis*
have $x = z$ **using** $\langle x = y \rangle \langle y = z \rangle$ **by** *metis*
show *?thesis* **using** $\langle A \approx C \rangle \langle x = z \rangle$ $X \ Z$
using *ptrm-alpha-equiv.fn1* **by** *metis*

next
case 2
have $x \neq z$ **using** $\langle x = y \rangle \langle y \neq z \rangle$ **by** *metis*
have $A \approx [x \leftrightarrow z] \cdot C$ **using** $\langle A \approx B \rangle \langle B \approx [y \leftrightarrow z] \cdot C \rangle \langle x = y \rangle$ $IH \ *$

by *metis*
have $x \notin \text{ptrm-fvs } C$ **using** $\langle x = y \rangle \langle y \notin \text{ptrm-fvs } C \rangle$ **by** *metis*
thus *?thesis* **using** $\langle x \neq z \rangle \langle A \approx [x \leftrightarrow z] \cdot C \rangle \langle x \notin \text{ptrm-fvs } C \rangle$ $X \ Z$
using *ptrm-alpha-equiv.fn2* **by** *metis*

next
case 3
have $x \neq z$ **using** $\langle x \neq y \rangle \langle y = z \rangle$ **by** *metis*
have $[x \leftrightarrow y] \cdot B \approx [x \leftrightarrow y] \cdot C$ **using** $\langle B \approx C \rangle$ *ptrm-alpha-equiv-prm* **by**

metis
have $A \approx [x \leftrightarrow z] \cdot C$
using $\langle A \approx [x \leftrightarrow y] \cdot B \rangle \langle [x \leftrightarrow y] \cdot B \approx [x \leftrightarrow y] \cdot C \rangle \langle y = z \rangle$ $IH \ *$
by *metis*
have $x \notin \text{ptrm-fvs } C$ **using** $\langle B \approx C \rangle \langle x \notin \text{ptrm-fvs } B \rangle$ *ptrm-alpha-equiv-fvs*

by *metis*

```

thus ?thesis using ⟨ $x \neq z$ ⟩ ⟨ $A \approx [x \leftrightarrow z] \cdot C$ ⟩ ⟨ $x \notin \text{ptrm-fvs } C$ ⟩  $X Z$ 
using ptrm-alpha-equiv.fn2 by metis
next
case 4
have  $[x \leftrightarrow y] \cdot B \approx [x \leftrightarrow y] \cdot [y \leftrightarrow z] \cdot C$ 
using ⟨ $B \approx [y \leftrightarrow z] \cdot C$ ⟩ ptrm-alpha-equiv-prm by metis
hence  $A \approx [x \leftrightarrow y] \cdot [y \leftrightarrow z] \cdot C$ 
using ⟨ $A \approx [x \leftrightarrow y] \cdot B$ ⟩ IH * by metis
hence  $A \approx ([x \leftrightarrow y] \diamond [y \leftrightarrow z]) \cdot C$  using ptrm-prm-apply-compose by
metis
hence  $A \approx ([x \leftrightarrow y] \diamond [y \leftrightarrow x]) \cdot C$  using ⟨ $x = z$ ⟩ by metis
hence  $A \approx ([x \leftrightarrow y] \diamond [x \leftrightarrow y]) \cdot C$  using prm-unit-commutes by metis
hence  $A \approx \varepsilon \cdot C$  using ⟨ $x = z$ ⟩ prm-unit-involution by metis
hence  $A \approx C$  using ptrm-prm-apply-id by metis

thus ?thesis using ⟨ $x = z$ ⟩ ⟨ $A \approx C$ ⟩  $X Z$ 
using ptrm-alpha-equiv.fn1 by metis
next
case 5
have  $x \notin \text{ptrm-fvs } C$  proof –
have  $\text{ptrm-fvs } B = \text{ptrm-fvs } ([y \leftrightarrow z] \cdot C)$ 
using ptrm-alpha-equiv-fvs ⟨ $B \approx [y \leftrightarrow z] \cdot C$ ⟩ by metis
hence  $x \notin \text{ptrm-fvs } ([y \leftrightarrow z] \cdot C)$  using ⟨ $x \notin \text{ptrm-fvs } B$ ⟩ by auto
hence  $x \notin [y \leftrightarrow z] \{\$\}$  ptrm-fvs  $C$  using ptrm-prm-fvs by metis
consider  $z \in \text{ptrm-fvs } C \mid z \notin \text{ptrm-fvs } C$  by auto
thus ?thesis proof(cases)
case 1
hence  $[y \leftrightarrow z] \{\$\}$  ptrm-fvs  $C = \text{ptrm-fvs } C - \{z\} \cup \{y\}$ 
using prm-set-unit-action prm-unit-commutes
and ⟨ $z \in \text{ptrm-fvs } C$ ⟩ ⟨ $y \notin \text{ptrm-fvs } C$ ⟩ by metis
hence  $x \notin \text{ptrm-fvs } C - \{z\} \cup \{y\}$  using ⟨ $x \notin [y \leftrightarrow z] \{\$\}$  ptrm-fvs
 $C$ ⟩ by auto
hence  $x \notin \text{ptrm-fvs } C - \{z\}$  using ⟨ $x \neq y$ ⟩ by auto
thus ?thesis using ⟨ $x \neq z$ ⟩ by auto
next
case 2
hence  $[y \leftrightarrow z] \{\$\}$  ptrm-fvs  $C = \text{ptrm-fvs } C$  using prm-set-unit-inaction
⟨ $y \notin \text{ptrm-fvs } C$ ⟩ by metis
thus ?thesis using ⟨ $x \notin [y \leftrightarrow z] \{\$\}$  ptrm-fvs  $C$ ⟩ by auto
next
qed
qed

have  $A \approx [x \leftrightarrow z] \cdot C$  proof –
have  $A \approx ([x \leftrightarrow y] \diamond [y \leftrightarrow z]) \cdot C$ 
using IH * ⟨ $A \approx [x \leftrightarrow y] \cdot B$ ⟩ ⟨ $B \approx [y \leftrightarrow z] \cdot C$ ⟩
and ptrm-alpha-equiv-prm ptrm-prm-apply-compose by metis

have  $([x \leftrightarrow y] \diamond [y \leftrightarrow z]) \cdot C \approx [x \leftrightarrow z] \cdot C$  proof –

```

have $ds ([x \leftrightarrow y] \diamond [y \leftrightarrow z]) [x \leftrightarrow z] = \{x, y\}$
using $\langle x \neq y \rangle \langle y \neq z \rangle \langle x \neq z \rangle$ *prm-disagreement-composition* **by** *metis*

hence $\bigwedge a. a \in ds ([x \leftrightarrow y] \diamond [y \leftrightarrow z]) [x \leftrightarrow z] \implies a \notin ptrm-fvs C$
using $\langle x \notin ptrm-fvs C \rangle \langle y \notin ptrm-fvs C \rangle$
using *Diff-iff Diff-insert-absorb insert-iff* **by** *auto*
thus *?thesis* **using** *ptrm-prm-agreement-equiv* **by** *metis*
qed

thus *?thesis* **using** *IH* *
using $\langle A \approx ([x \leftrightarrow y] \diamond [y \leftrightarrow z]) \cdot C \rangle \langle ([x \leftrightarrow y] \diamond [y \leftrightarrow z]) \cdot C \approx [x \leftrightarrow z] \cdot C \rangle$
by *metis*
qed

show *?thesis* **using** $\langle x \neq z \rangle \langle A \approx [x \leftrightarrow z] \cdot C \rangle \langle x \notin ptrm-fvs C \rangle X Z$
using *ptrm-alpha-equiv.fn2* **by** *metis*

next
qed
next
case (*PPair A B*)
obtain $C D$ **where** $Y = PPair C D$ **and** $A \approx C$ **and** $B \approx D$
using *pairE* $\langle X = PPair A B \rangle \langle X \approx Y \rangle$ **by** *metis*
hence $PPair C D \approx Z$ **using** $\langle Y \approx Z \rangle$ **by** *simp*
from *this* **obtain** $E F$ **where** $Z = PPair E F$ **and** $C \approx E$ **and** $D \approx F$ **using** *pairE* **by** *metis*

have $size A < size X$ **and** $size B < size X$ **using** $\langle X = PPair A B \rangle$ **by** *auto*
hence $A \approx E$ **and** $B \approx F$ **using** *IH* $\langle A \approx C \rangle \langle C \approx E \rangle \langle B \approx D \rangle \langle D \approx F \rangle$
by *auto*
thus *?thesis* **using** $\langle X = PPair A B \rangle \langle Z = PPair E F \rangle$ *ptrm-alpha-equiv.pair*
by *metis*

next
case (*PFst P*)
obtain Q **where** $Y = PFst Q P \approx Q$ **using** *fstE* $\langle X = PFst P \rangle \langle X \approx Y \rangle$
by *metis*
obtain R **where** $Z = PFst R Q \approx R$ **using** *fstE* $\langle Y = PFst Q \rangle \langle Y \approx Z \rangle$
by *metis*

have $size P < size X$ **using** $\langle X = PFst P \rangle$ **by** *auto*
hence $P \approx R$ **using** *IH* $\langle P \approx Q \rangle \langle Q \approx R \rangle$ **by** *metis*
thus *?thesis* **using** $\langle X = PFst P \rangle \langle Z = PFst R \rangle$ *ptrm-alpha-equiv.fst* **by** *metis*

next
case (*PSnd P*)
obtain Q **where** $Y = PSnd Q P \approx Q$ **using** *sndE* $\langle X = PSnd P \rangle \langle X \approx Y \rangle$
by *metis*
obtain R **where** $Z = PSnd R Q \approx R$ **using** *sndE* $\langle Y = PSnd Q \rangle \langle Y \approx Z \rangle$

by metis

```
    have size P < size X using ⟨X = PSnd P⟩ by auto
    hence P ≈ R using IH ⟨P ≈ Q⟩ ⟨Q ≈ R⟩ by metis
    thus ?thesis using ⟨X = PSnd P⟩ ⟨Z = PSnd R⟩ ptrm-alpha-equiv.snd by
metis
  next
  qed
qed
```

corollary ptrm-alpha-equiv-transp:

```
  shows transp ptrm-alpha-equiv
  unfolding transp-def using ptrm-alpha-equiv-transitive by auto
```

type-synonym 'a typing-ctx = 'a \rightarrow type

```
fun ptrm-infer-type :: 'a typing-ctx  $\Rightarrow$  'a ptrm  $\Rightarrow$  type option where
  ptrm-infer-type  $\Gamma$  PUnit = Some TUnit
| ptrm-infer-type  $\Gamma$  (PVar x) =  $\Gamma$  x
| ptrm-infer-type  $\Gamma$  (PApp A B) = (case (ptrm-infer-type  $\Gamma$  A, ptrm-infer-type  $\Gamma$ 
B) of
  (Some (TArr  $\tau$   $\sigma$ ), Some  $\tau'$ )  $\Rightarrow$  (if  $\tau = \tau'$  then Some  $\sigma$  else None)
| -  $\Rightarrow$  None
)
| ptrm-infer-type  $\Gamma$  (PFn x  $\tau$  A) = (case ptrm-infer-type ( $\Gamma(x \mapsto \tau)$ ) A of
  Some  $\sigma \Rightarrow$  Some (TArr  $\tau$   $\sigma$ )
| None  $\Rightarrow$  None
)
| ptrm-infer-type  $\Gamma$  (PPair A B) = (case (ptrm-infer-type  $\Gamma$  A, ptrm-infer-type  $\Gamma$ 
B) of
  (Some  $\tau$ , Some  $\sigma$ )  $\Rightarrow$  Some (TPair  $\tau$   $\sigma$ )
| -  $\Rightarrow$  None
)
| ptrm-infer-type  $\Gamma$  (PFst P) = (case ptrm-infer-type  $\Gamma$  P of
  (Some (TPair  $\tau$   $\sigma$ ))  $\Rightarrow$  Some  $\tau$ 
| -  $\Rightarrow$  None
)
| ptrm-infer-type  $\Gamma$  (PSnd P) = (case ptrm-infer-type  $\Gamma$  P of
  (Some (TPair  $\tau$   $\sigma$ ))  $\Rightarrow$  Some  $\sigma$ 
| -  $\Rightarrow$  None
)
```

lemma ptrm-infer-type-swp-types:

```
  assumes a  $\neq$  b
  shows ptrm-infer-type ( $\Gamma(a \mapsto T, b \mapsto S)$ ) X = ptrm-infer-type ( $\Gamma(a \mapsto S, b \mapsto$ 
T)) ([a  $\leftrightarrow$  b]  $\cdot$  X)
  using assms proof(induction X arbitrary: T S  $\Gamma$ )
  case (PUnit)

```

```

thus ?case by simp
next
case (PVar x)
  consider  $x = a \mid x = b \mid x \neq a \wedge x \neq b$  by auto
  thus ?case proof(cases)
    assume  $x = a$ 
    thus ?thesis using  $\langle a \neq b \rangle$  by (simp add: prm-unit-action)
    next

    assume  $x = b$ 
    thus ?thesis using  $\langle a \neq b \rangle$ 
      using prm-unit-action prm-unit-commutes fun-upd-same fun-upd-twist
      by (metis ptrm-apply-prm.simps(2) ptrm-infer-type.simps(2))
    next

    assume  $x \neq a \wedge x \neq b$ 
    thus ?thesis by (simp add: prm-unit-inaction)
    next
  qed
next
case (PApp A B)
  thus ?case by simp
next
case (PFn x  $\tau$  A)
  hence *:
    ptrm-infer-type ( $\Gamma(a \mapsto T, b \mapsto S)$ ) A = ptrm-infer-type ( $\Gamma(a \mapsto S, b \mapsto T)$ )
    ( $[a \leftrightarrow b] \cdot A$ )
    for T S  $\Gamma$ 
    by metis

  consider  $x = a \mid x = b \mid x \neq a \wedge x \neq b$  by auto
  thus ?case proof(cases)
    case 1
      hence
        ptrm-infer-type ( $\Gamma(a \mapsto S, b \mapsto T)$ ) ( $[a \leftrightarrow b] \cdot \text{PFn } x \tau A$ )
        = ptrm-infer-type ( $\Gamma(a \mapsto S, b \mapsto T)$ ) (PFn b  $\tau$  ( $[a \leftrightarrow b] \cdot A$ ))
        using prm-unit-action ptrm-apply-prm.simps(4) by metis
        moreover have ... = (case ptrm-infer-type ( $\Gamma(a \mapsto S, b \mapsto \tau)$ ) ( $[a \leftrightarrow b] \cdot$ 
        A) of None  $\Rightarrow$  None | Some  $\sigma \Rightarrow$  Some (TArr  $\tau \sigma$ ))
        by simp
        moreover have ... = (case ptrm-infer-type ( $\Gamma(a \mapsto \tau, b \mapsto S)$ ) A of None
         $\Rightarrow$  None | Some  $\sigma \Rightarrow$  Some (TArr  $\tau \sigma$ ))
        using * by metis
        moreover have ... = (case ptrm-infer-type ( $\Gamma(b \mapsto S, a \mapsto T, a \mapsto \tau)$ ) A
        of None  $\Rightarrow$  None | Some  $\sigma \Rightarrow$  Some (TArr  $\tau \sigma$ ))
        using  $\langle a \neq b \rangle$  fun-upd-twist fun-upd-upd by metis
        moreover have ... = ptrm-infer-type ( $\Gamma(b \mapsto S, a \mapsto T)$ ) (PFn x  $\tau$  A)
        using  $\langle x = a \rangle$  by simp
        moreover have ... = ptrm-infer-type ( $\Gamma(a \mapsto T, b \mapsto S)$ ) (PFn x  $\tau$  A)

```

using $\langle a \neq b \rangle$ *fun-upd-twist* **by** *metis*
ultimately show *?thesis* **by** *metis*
next
case 2
hence
 $\text{ptrm-infer-type } (\Gamma(a \mapsto S, b \mapsto T)) ([a \leftrightarrow b] \cdot \text{PFn } x \tau A)$
 $= \text{ptrm-infer-type } (\Gamma(a \mapsto S, b \mapsto T)) (\text{PFn } a \tau ([a \leftrightarrow b] \cdot A))$
using *prm-unit-action prm-unit-commutes ptrm-apply-prm.simps(4)* **by**
metis
moreover have ... = (case *ptrm-infer-type* $(\Gamma(a \mapsto S, b \mapsto T, a \mapsto \tau)) ([a \leftrightarrow b] \cdot A)$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
by *simp*
moreover have ... = (case *ptrm-infer-type* $(\Gamma(a \mapsto \tau, b \mapsto T)) ([a \leftrightarrow b] \cdot A)$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
using *fun-upd-upd fun-upd-twist* $\langle a \neq b \rangle$ **by** *metis*
moreover have ... = (case *ptrm-infer-type* $(\Gamma(a \mapsto T, b \mapsto \tau)) A$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
using * **by** *metis*
moreover have ... = (case *ptrm-infer-type* $(\Gamma(a \mapsto T, b \mapsto S, b \mapsto \tau)) A$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
using $\langle a \neq b \rangle$ *fun-upd-upd* **by** *metis*
moreover have ... = *ptrm-infer-type* $(\Gamma(b \mapsto S, a \mapsto T)) (\text{PFn } x \tau A)$
using $\langle x = b \rangle$ **by** *simp*
moreover have ... = *ptrm-infer-type* $(\Gamma(a \mapsto T, b \mapsto S)) (\text{PFn } x \tau A)$
using $\langle a \neq b \rangle$ *fun-upd-twist* **by** *metis*
ultimately show *?thesis* **by** *metis*
next
case 3
hence $x \neq a \ x \neq b$ **by** *auto*
hence
 $\text{ptrm-infer-type } (\Gamma(a \mapsto S, b \mapsto T)) ([a \leftrightarrow b] \cdot \text{PFn } x \tau A)$
 $= \text{ptrm-infer-type } (\Gamma(a \mapsto S, b \mapsto T)) (\text{PFn } x \tau ([a \leftrightarrow b] \cdot A))$
by (*simp add: prm-unit-inaction*)
moreover have ... = (case *ptrm-infer-type* $(\Gamma(a \mapsto S, b \mapsto T, x \mapsto \tau)) ([a \leftrightarrow b] \cdot A)$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
by *simp*
moreover have ... = (case *ptrm-infer-type* $(\Gamma(x \mapsto \tau, a \mapsto S, b \mapsto T)) ([a \leftrightarrow b] \cdot A)$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
using $\langle x \neq a \rangle \langle x \neq b \rangle$ *fun-upd-twist* **by** *metis*
moreover have ... = (case *ptrm-infer-type* $(\Gamma(x \mapsto \tau, a \mapsto T, b \mapsto S)) A$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
using * **by** *metis*
moreover have ... = (case *ptrm-infer-type* $(\Gamma(a \mapsto T, b \mapsto S, x \mapsto \tau)) A$ of *None* \Rightarrow *None* | *Some* $\sigma \Rightarrow$ *Some* $(\text{TArr } \tau \sigma)$)
using $\langle x \neq a \rangle \langle x \neq b \rangle$ *fun-upd-twist* **by** *metis*
moreover have ... = *ptrm-infer-type* $(\Gamma(a \mapsto T, b \mapsto S)) (\text{PFn } x \tau A)$ **by**
simp
ultimately show *?thesis* **by** *metis*
next

```

    qed
  next
  case (PPair A B)
    thus ?case by simp
  next
  case (PFst P)
    thus ?case by simp
  next
  case (PSnd P)
    thus ?case by simp
  next
  qed

```

lemma *ptrm-infer-type-swp*:

```

  assumes  $a \neq b$   $b \notin \text{ptrm-fvs } X$ 
  shows  $\text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) X = \text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) ([a \leftrightarrow b] \cdot X)$ 
  using assms proof(induction X arbitrary:  $\tau \Gamma$ )
  case (PUnit)
    thus ?case by simp
  next
  case (PVar x)
    hence  $x \neq b$  by simp
    consider  $x = a \mid x \neq a$  by auto
    thus ?case proof(cases)
      case 1
        hence  $[a \leftrightarrow b] \cdot (PVar x) = PVar b$ 
        and  $\text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) (PVar x) = \text{Some } \tau$  using prm-unit-action
      by auto
        thus ?thesis by auto
      next
        case 2
          hence  $*$ :  $[a \leftrightarrow b] \cdot PVar x = PVar x$  using  $\langle x \neq b \rangle$  prm-unit-inaction by
          simp
          consider  $\exists \sigma. \Gamma x = \text{Some } \sigma \mid \Gamma x = \text{None}$  by auto
          thus ?thesis proof(cases)
            assume  $\exists \sigma. \Gamma x = \text{Some } \sigma$ 
            from this obtain  $\sigma$  where  $\Gamma x = \text{Some } \sigma$  by auto
            thus ?thesis using  $*$   $\langle x \neq a \rangle \langle x \neq b \rangle$  by auto
            next
              assume  $\Gamma x = \text{None}$ 
              thus ?thesis using  $*$   $\langle x \neq a \rangle \langle x \neq b \rangle$  by auto
            qed
          next
            qed
          next
            qed
          next
          case (PApp A B)

```

have $b \notin \text{ptrm-fvs } A$ **and** $b \notin \text{ptrm-fvs } B$ **using** $PApp.premis$ **by** $auto$
hence $\text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) A = \text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) ([a \leftrightarrow b] \cdot A)$
and $\text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) B = \text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) ([a \leftrightarrow b] \cdot B)$
using $PApp.IH$ $assms$ **by** $metis+$

thus $?case$ **by** $(metis \text{ptrm-apply-prm.simps}(3) \text{ptrm-infer-type.simps}(3))$
next
case $(PFn x \sigma A)$
consider $b \neq x \wedge b \notin \text{ptrm-fvs } A \mid b = x$ **using** $PFn.premis$ **by** $auto$
thus $?case$ **proof** $(cases)$
case 1
hence $b \neq x \wedge b \notin \text{ptrm-fvs } A$ **by** $auto$
hence $*$: $\bigwedge \tau \Gamma. \text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) A = \text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) ([a \leftrightarrow b] \cdot A)$
using $PFn.IH$ $assms$ **by** $metis$
consider $a = x \mid a \neq x$ **by** $auto$
thus $?thesis$ **proof** $(cases)$
case 1
hence $\text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) (PFn x \sigma A) = \text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) (PFn a \sigma A)$
and
 $\text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) ([a \leftrightarrow b] \cdot PFn x \sigma A) =$
 $\text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) (PFn b \sigma ([a \leftrightarrow b] \cdot A))$
by $(auto \text{ simp add: prn-unit-action})$
thus $?thesis$ **using** $* \text{ptrm-infer-type.simps}(4)$ $fun-upd-upd$ **by** $metis$
next

case 2
hence
 $\text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) ([a \leftrightarrow b] \cdot PFn x \sigma A)$
 $= \text{ptrm-infer-type } (\Gamma(b \mapsto \tau)) (PFn x \sigma ([a \leftrightarrow b] \cdot A))$
using $\langle b \neq x \rangle$ **by** $(simp \text{ add: prn-unit-inaction})$
moreover have $\dots = (case \text{ptrm-infer-type } (\Gamma(b \mapsto \tau, x \mapsto \sigma)) ([a \leftrightarrow b] \cdot A) \text{ of } None \Rightarrow None \mid Some \sigma' \Rightarrow Some (TArr \sigma \sigma'))$
by $simp$
moreover have $\dots = (case \text{ptrm-infer-type } (\Gamma(x \mapsto \sigma, b \mapsto \tau)) ([a \leftrightarrow b] \cdot A) \text{ of } None \Rightarrow None \mid Some \sigma' \Rightarrow Some (TArr \sigma \sigma'))$
using $\langle b \neq x \rangle$ $fun-upd-twist$ **by** $metis$
moreover have $\dots = (case \text{ptrm-infer-type } (\Gamma(x \mapsto \sigma, a \mapsto \tau)) A \text{ of } None \Rightarrow None \mid Some \sigma' \Rightarrow Some (TArr \sigma \sigma'))$
using $*$ **by** $metis$
moreover have $\dots = (case \text{ptrm-infer-type } (\Gamma(a \mapsto \tau, x \mapsto \sigma)) A \text{ of } None \Rightarrow None \mid Some \sigma' \Rightarrow Some (TArr \sigma \sigma'))$
using $\langle a \neq x \rangle$ $fun-upd-twist$ **by** $metis$
moreover have $\dots = \text{ptrm-infer-type } (\Gamma(a \mapsto \tau)) (PFn x \sigma A)$
by $simp$
ultimately show $?thesis$ **by** $metis$

```

    next
  qed
next

case 2
  hence  $a \neq x$  using assms by auto
  have
    ptrm-infer-type ( $\Gamma(a \mapsto \tau, b \mapsto \sigma)$ )  $A =$ 
    ptrm-infer-type ( $\Gamma(b \mapsto \tau, a \mapsto \sigma)$ ) ( $[a \leftrightarrow b] \cdot A$ )
  using ptrm-infer-type-swp-types using  $\langle a \neq b \rangle$  fun-upd-twist by metis
  thus ?thesis
  using  $\langle b = x \rangle$  prm-unit-action prm-unit-commutes
  using ptrm-infer-type.simps(4) ptrm-apply-prm.simps(4) by metis
next
qed
next
case (PPair A B)
  thus ?case by simp
next
case (PFst P)
  thus ?case by simp
next
case (PSnd P)
  thus ?case by simp
next
qed

lemma ptrm-infer-type-alpha-equiv:
  assumes  $X \approx Y$ 
  shows ptrm-infer-type  $\Gamma X =$  ptrm-infer-type  $\Gamma Y$ 
using assms proof(induction arbitrary: \Gamma)
  case (fn2 a b A B T  $\Gamma$ )
    hence ptrm-infer-type ( $\Gamma(a \mapsto T)$ )  $A =$  ptrm-infer-type ( $\Gamma(b \mapsto T)$ )  $B$ 
    using ptrm-infer-type-swp prm-unit-commutes by metis
  thus ?case by simp
next
qed auto

end
theory SimplyTyped
imports PreSimplyTyped
begin

quotient-type 'a trm = 'a ptrm / ptrm-alpha-equiv
proof(rule equivpI)
  show reflp ptrm-alpha-equiv using ptrm-alpha-equiv-reflp.
  show symp ptrm-alpha-equiv using ptrm-alpha-equiv-symp.
  show transp ptrm-alpha-equiv using ptrm-alpha-equiv-transp.
qed

```

lift-definition *Unit* :: 'a trm is *PUnit*.
lift-definition *Var* :: 'a ⇒ 'a trm is *PVar*.
lift-definition *App* :: 'a trm ⇒ 'a trm ⇒ 'a trm is *PApp* using *ptrm-alpha-equiv.app*.
lift-definition *Fn* :: 'a ⇒ type ⇒ 'a trm ⇒ 'a trm is *PFn* using *ptrm-alpha-equiv.fn1*.
lift-definition *Pair* :: 'a trm ⇒ 'a trm ⇒ 'a trm is *PPair* using *ptrm-alpha-equiv.pair*.
lift-definition *Fst* :: 'a trm ⇒ 'a trm is *PFst* using *ptrm-alpha-equiv.fst*.
lift-definition *Snd* :: 'a trm ⇒ 'a trm is *PSnd* using *ptrm-alpha-equiv.snd*.
lift-definition *fvs* :: 'a trm ⇒ 'a set is *ptrm-fvs* using *ptrm-alpha-equiv.fvs*.
lift-definition *prm* :: 'a prm ⇒ 'a trm ⇒ 'a trm (infixr · 150) is *ptrm-apply-prm*
using *ptrm-alpha-equiv-prm*.
lift-definition *depth* :: 'a trm ⇒ nat is *size* using *ptrm-size-alpha-equiv*.

lemma *depth-prm*:
shows $depth (\pi \cdot A) = depth A$
by(*transfer*, *metis ptrm-size-prm*)

lemma *depth-app*:
shows $depth A < depth (App A B)$ $depth B < depth (App A B)$
by(*transfer*, *auto*)+

lemma *depth-fn*:
shows $depth A < depth (Fn x T A)$
by(*transfer*, *auto*)

lemma *depth-pair*:
shows $depth A < depth (Pair A B)$ $depth B < depth (Pair A B)$
by(*transfer*, *auto*)+

lemma *depth-fst*:
shows $depth P < depth (Fst P)$
by(*transfer*, *auto*)

lemma *depth-snd*:
shows $depth P < depth (Snd P)$
by(*transfer*, *auto*)

lemma *unit-not-var*:
shows $Unit \neq Var x$
proof(*transfer*)
fix $x :: 'a$
show $\neg PUnit \approx PVar x$
proof(*rule classical*)
assume $\neg \neg PUnit \approx PVar x$
hence *False* using *unitE* by *fastforce*
thus *?thesis* by *blast*
qed
qed

```

lemma unit-not-app:
  shows  $Unit \neq App\ A\ B$ 
proof(transfer)
  fix  $A\ B :: 'a\ ptrm$ 
  show  $\neg PUnit \approx PApp\ A\ B$ 
proof(rule classical)
  assume  $\neg\neg PUnit \approx PApp\ A\ B$ 
  hence False using unitE by fastforce
  thus ?thesis by blast
qed
qed

```

```

lemma unit-not-fn:
  shows  $Unit \neq Fn\ x\ T\ A$ 
proof(transfer)
  fix  $x :: 'a$  and  $T\ A$ 
  show  $\neg PUnit \approx PFn\ x\ T\ A$ 
proof(rule classical)
  assume  $\neg\neg PUnit \approx PFn\ x\ T\ A$ 
  hence False using unitE by fastforce
  thus ?thesis by blast
qed
qed

```

```

lemma unit-not-pair:
  shows  $Unit \neq Pair\ A\ B$ 
proof(transfer)
  fix  $A\ B :: 'a\ ptrm$ 
  show  $\neg PUnit \approx PPair\ A\ B$ 
proof(rule classical)
  assume  $\neg\neg PUnit \approx PPair\ A\ B$ 
  hence False using unitE by fastforce
  thus ?thesis by blast
qed
qed

```

```

lemma unit-not-fst:
  shows  $Unit \neq Fst\ P$ 
proof(transfer)
  fix  $P :: 'a\ ptrm$ 
  show  $\neg PUnit \approx PFst\ P$ 
proof(rule classical)
  assume  $\neg\neg PUnit \approx PFst\ P$ 
  hence False using unitE by fastforce
  thus ?thesis by blast
qed
qed

```

```

lemma unit-not-snd:

```

```

shows  $Unit \neq Snd P$ 
proof(transfer)
  fix  $P :: 'a ptrm$ 
  show  $\neg PUnit \approx PSnd P$ 
  proof(rule classical)
    assume  $\neg\neg PUnit \approx PSnd P$ 
    hence False using unitE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma var-not-app:
  shows  $Var x \neq App A B$ 
proof(transfer)
  fix  $x :: 'a$  and  $A B$ 
  show  $\neg PVar x \approx PApp A B$ 
  proof(rule classical)
    assume  $\neg\neg PVar x \approx PApp A B$ 
    hence False using varE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma var-not-fn:
  shows  $Var x \neq Fn y T A$ 
proof(transfer)
  fix  $x y :: 'a$  and  $T A$ 
  show  $\neg PVar x \approx PFn y T A$ 
  proof(rule classical)
    assume  $\neg\neg PVar x \approx PFn y T A$ 
    hence False using varE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma var-not-pair:
  shows  $Var x \neq Pair A B$ 
proof(transfer)
  fix  $x :: 'a$  and  $A B$ 
  show  $\neg PVar x \approx PPair A B$ 
  proof(rule classical)
    assume  $\neg\neg PVar x \approx PPair A B$ 
    hence False using varE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma var-not-fst:
  shows  $Var x \neq Fst P$ 

```

```

proof(transfer)
  fix  $x :: 'a$  and  $P$ 
  show  $\neg PVar\ x \approx PFst\ P$ 
  proof(rule classical)
    assume  $\neg\neg PVar\ x \approx PFst\ P$ 
    hence False using varE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma var-not-snd:
  shows  $Var\ x \neq Snd\ P$ 
proof(transfer)
  fix  $x :: 'a$  and  $P$ 
  show  $\neg PVar\ x \approx PSnd\ P$ 
  proof(rule classical)
    assume  $\neg\neg PVar\ x \approx PSnd\ P$ 
    hence False using varE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma app-not-fn:
  shows  $App\ A\ B \neq Fn\ y\ T\ X$ 
proof(transfer)
  fix  $y :: 'a$  and  $A\ B\ T\ X$ 
  show  $\neg PApp\ A\ B \approx PFn\ y\ T\ X$ 
  proof(rule classical)
    assume  $\neg\neg PApp\ A\ B \approx PFn\ y\ T\ X$ 
    hence False using appE by auto
    thus ?thesis by blast
  qed
qed

```

```

lemma app-not-pair:
  shows  $App\ A\ B \neq Pair\ C\ D$ 
proof(transfer)
  fix  $A\ B\ C\ D :: 'a\ ptrm$ 
  show  $\neg PApp\ A\ B \approx PPair\ C\ D$ 
  proof(rule classical)
    assume  $\neg\neg PApp\ A\ B \approx PPair\ C\ D$ 
    hence False using appE by auto
    thus ?thesis by blast
  qed
qed

```

```

lemma app-not-fst:
  shows  $App\ A\ B \neq Fst\ P$ 
proof(transfer)

```

```

fix A B P :: 'a ptrm
show  $\neg$ PAApp A B  $\approx$  PFst P
proof(rule classical)
  assume  $\neg$  $\neg$ PAApp A B  $\approx$  PFst P
  hence False using appE by auto
  thus ?thesis by blast
qed
qed

```

```

lemma app-not-snd:
  shows App A B  $\neq$  Snd P
proof(transfer)
  fix A B P :: 'a ptrm
  show  $\neg$ PAApp A B  $\approx$  PSnd P
  proof(rule classical)
    assume  $\neg$  $\neg$ PAApp A B  $\approx$  PSnd P
    hence False using appE by auto
    thus ?thesis by blast
  qed
qed

```

```

lemma fn-not-pair:
  shows Fn x T A  $\neq$  Pair C D
proof(transfer)
  fix x :: 'a and T A C D
  show  $\neg$ PFn x T A  $\approx$  PPair C D
  proof(rule classical)
    assume  $\neg$  $\neg$ PFn x T A  $\approx$  PPair C D
    hence False using fnE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma fn-not-fst:
  shows Fn x T A  $\neq$  Fst P
proof(transfer)
  fix x :: 'a and T A P
  show  $\neg$ PFn x T A  $\approx$  PFst P
  proof(rule classical)
    assume  $\neg$  $\neg$ PFn x T A  $\approx$  PFst P
    hence False using fnE by fastforce
    thus ?thesis by blast
  qed
qed

```

```

lemma fn-not-snd:
  shows Fn x T A  $\neq$  Snd P
proof(transfer)
  fix x :: 'a and T A P

```

```

show  $\neg PFn\ x\ T\ A \approx PSnd\ P$ 
proof(rule classical)
  assume  $\neg\neg PFn\ x\ T\ A \approx PSnd\ P$ 
  hence False using fnE by fastforce
  thus ?thesis by blast
qed
qed

```

```

lemma pair-not-fst:
  shows  $Pair\ A\ B \neq Fst\ P$ 
proof(transfer)
  fix  $A\ B\ P :: 'a\ ptrm$ 
  show  $\neg PPair\ A\ B \approx PFst\ P$ 
  proof(rule classical)
    assume  $\neg\neg PPair\ A\ B \approx PFst\ P$ 
    hence False using pairE by auto
    thus ?thesis by blast
  qed
qed

```

```

lemma pair-not-snd:
  shows  $Pair\ A\ B \neq Snd\ P$ 
proof(transfer)
  fix  $A\ B\ P :: 'a\ ptrm$ 
  show  $\neg PPair\ A\ B \approx PSnd\ P$ 
  proof(rule classical)
    assume  $\neg\neg PPair\ A\ B \approx PSnd\ P$ 
    hence False using pairE by auto
    thus ?thesis by blast
  qed
qed

```

```

lemma fst-not-snd:
  shows  $Fst\ P \neq Snd\ Q$ 
proof(transfer)
  fix  $P\ Q :: 'a\ ptrm$ 
  show  $\neg PFst\ P \approx PSnd\ Q$ 
  proof(rule classical)
    assume  $\neg\neg PFst\ P \approx PSnd\ Q$ 
    hence False using fstE by auto
    thus ?thesis by blast
  qed
qed

```

```

lemma trm-simp:
  shows
     $Var\ x = Var\ y \implies x = y$ 
     $App\ A\ B = App\ C\ D \implies A = C$ 
     $App\ A\ B = App\ C\ D \implies B = D$ 

```

$Fn\ x\ T\ A = Fn\ y\ S\ B \implies$
 $(x = y \wedge T = S \wedge A = B) \vee (x \neq y \wedge T = S \wedge x \notin fvs\ B \wedge A = [x \leftrightarrow y] \cdot B)$
 $Pair\ A\ B = Pair\ C\ D \implies A = C$
 $Pair\ A\ B = Pair\ C\ D \implies B = D$
 $Fst\ P = Fst\ Q \implies P = Q$
 $Snd\ P = Snd\ Q \implies P = Q$

proof –

show $Var\ x = Var\ y \implies x = y$ **by** $(transfer, insert\ ptrm.inject\ varE, fastforce)$
show $App\ A\ B = App\ C\ D \implies A = C$ **by** $(transfer, insert\ ptrm.inject\ appE, auto)$
show $App\ A\ B = App\ C\ D \implies B = D$ **by** $(transfer, insert\ ptrm.inject\ appE, auto)$
show $Pair\ A\ B = Pair\ C\ D \implies A = C$ **by** $(transfer, insert\ ptrm.inject\ pairE, auto)$
show $Pair\ A\ B = Pair\ C\ D \implies B = D$ **by** $(transfer, insert\ ptrm.inject\ pairE, auto)$
show $Fst\ P = Fst\ Q \implies P = Q$ **by** $(transfer, insert\ ptrm.inject\ fstE, auto)$
show $Snd\ P = Snd\ Q \implies P = Q$ **by** $(transfer, insert\ ptrm.inject\ sndE, auto)$
show $Fn\ x\ T\ A = Fn\ y\ S\ B \implies$
 $(x = y \wedge T = S \wedge A = B) \vee (x \neq y \wedge T = S \wedge x \notin fvs\ B \wedge A = [x \leftrightarrow y] \cdot B)$

proof $(transfer')$

fix $x\ y :: 'a$ **and** $T\ S :: type$ **and** $A\ B :: 'a\ ptrm$
assume $*$: $PFn\ x\ T\ A \approx PFn\ y\ S\ B$
thus $x = y \wedge T = S \wedge A \approx B \vee x \neq y \wedge T = S \wedge x \notin ptrm-fvs\ B \wedge A \approx [x \leftrightarrow y] \cdot B$
proof $(induction\ rule: fnE[where\ x=x\ and\ T=T\ and\ A=A\ and\ Y=PFn\ y\ S\ B], metis\ *)$
case $(2\ C)$
thus $?case$ **by** $simp$
next
case $(3\ z\ C)$
thus $?case$ **by** $simp$
next
qed
qed
qed

lemma $fn-eq$:

assumes $x \neq y\ x \notin fvs\ B\ A = [x \leftrightarrow y] \cdot B$
shows $Fn\ x\ T\ A = Fn\ y\ T\ B$
using $assms$ **by** $(transfer', metis\ ptrm-alpha-equiv.fn2)$

lemma $trm-prm-simp$:

shows
 $\pi \cdot Unit = Unit$
 $\pi \cdot Var\ x = Var\ (\pi\ \$\ x)$
 $\pi \cdot App\ A\ B = App\ (\pi \cdot A)\ (\pi \cdot B)$

```

     $\pi \cdot \text{Fn } x \ T \ A = \text{Fn } (\pi \ \$ \ x) \ T \ (\pi \cdot A)$ 
     $\pi \cdot \text{Pair } A \ B = \text{Pair } (\pi \cdot A) \ (\pi \cdot B)$ 
     $\pi \cdot \text{Fst } P = \text{Fst } (\pi \cdot P)$ 
     $\pi \cdot \text{Snd } P = \text{Snd } (\pi \cdot P)$ 
apply (transfer, auto simp add: ptrm-alpha-equiv-reflexive)
apply (transfer', auto simp add: ptrm-alpha-equiv-reflexive)
apply ((transfer, auto simp add: ptrm-alpha-equiv-reflexive)+)
done

lemma trm-prm-apply-compose:
  shows  $\pi \cdot \sigma \cdot A = (\pi \diamond \sigma) \cdot A$ 
by(transfer', metis ptrm-prm-apply-compose ptrm-alpha-equiv-reflexive)

lemma fvs-finite:
  shows finite (fvs M)
by(transfer, metis ptrm-fvs-finite)

lemma fvs-simp:
  shows
    fvs Unit = {} and
    fvs (Var x) = {x}
    fvs (App A B) = fvs A  $\cup$  fvs B
    fvs (Fn x T A) = fvs A - {x}
    fvs (Pair A B) = fvs A  $\cup$  fvs B
    fvs (Fst P) = fvs P
    fvs (Snd P) = fvs P
by((transfer, simp)+)

lemma var-prm-action:
  shows  $[a \leftrightarrow b] \cdot \text{Var } a = \text{Var } b$ 
by(transfer', simp add: prm-unit-action ptrm-alpha-equiv.intros)

lemma var-prm-inaction:
  assumes  $a \neq x \ b \neq x$ 
  shows  $[a \leftrightarrow b] \cdot \text{Var } x = \text{Var } x$ 
using assms by(transfer', simp add: prm-unit-inaction ptrm-alpha-equiv.intros)

lemma trm-prm-apply-id:
  shows  $\varepsilon \cdot M = M$ 
by(transfer', auto simp add: ptrm-prm-apply-id)

lemma trm-prm-unit-inaction:
  assumes  $a \notin \text{fvs } X \ b \notin \text{fvs } X$ 
  shows  $[a \leftrightarrow b] \cdot X = X$ 
using assms by(transfer', metis ptrm-prm-unit-inaction)

lemma trm-prm-agreement-equiv:
  assumes  $\bigwedge a. a \in \text{ds } \pi \ \sigma \implies a \notin \text{fvs } M$ 
  shows  $\pi \cdot M = \sigma \cdot M$ 

```

using *assms* **by**(*transfer*, *metis ptrm-prm-agreement-equiv*)

lemma *trm-induct*:

fixes $P :: 'a \text{ trm} \Rightarrow \text{bool}$

assumes

$P \text{ Unit}$

$\bigwedge x. P (\text{Var } x)$

$\bigwedge A B. \llbracket P A; P B \rrbracket \Longrightarrow P (\text{App } A B)$

$\bigwedge x T A. P A \Longrightarrow P (\text{Fn } x T A)$

$\bigwedge A B. \llbracket P A; P B \rrbracket \Longrightarrow P (\text{Pair } A B)$

$\bigwedge A. P A \Longrightarrow P (\text{Fst } A)$

$\bigwedge A. P A \Longrightarrow P (\text{Snd } A)$

shows $P M$

proof –

have $\bigwedge X. P (\text{abs-trm } X)$

proof(*rule ptrm.induct*)

show $P (\text{abs-trm } P \text{Unit})$

using *assms(1) Unit.abs-eq* **by** *metis*

show $P (\text{abs-trm } (P \text{Var } x))$ **for** x

using *assms(2) Var.abs-eq* **by** *metis*

show $\llbracket P (\text{abs-trm } A); P (\text{abs-trm } B) \rrbracket \Longrightarrow P (\text{abs-trm } (P \text{App } A B))$ **for** $A B$

using *assms(3) App.abs-eq* **by** *metis*

show $P (\text{abs-trm } A) \Longrightarrow P (\text{abs-trm } (P \text{Fn } x T A))$ **for** $x T A$

using *assms(4) Fn.abs-eq* **by** *metis*

show $\llbracket P (\text{abs-trm } A); P (\text{abs-trm } B) \rrbracket \Longrightarrow P (\text{abs-trm } (P \text{Pair } A B))$ **for** $A B$

using *assms(5) Pair.abs-eq* **by** *metis*

show $P (\text{abs-trm } A) \Longrightarrow P (\text{abs-trm } (P \text{Fst } A))$ **for** A

using *assms(6) Fst.abs-eq* **by** *metis*

show $P (\text{abs-trm } A) \Longrightarrow P (\text{abs-trm } (P \text{Snd } A))$ **for** A

using *assms(7) Snd.abs-eq* **by** *metis*

qed

thus *?thesis* **using** *trm.abs-induct* **by** *auto*

qed

lemma *trm-cases*:

assumes

$M = \text{Unit} \Longrightarrow P M$

$\bigwedge x. M = \text{Var } x \Longrightarrow P M$

$\bigwedge A B. M = \text{App } A B \Longrightarrow P M$

$\bigwedge x T A. M = \text{Fn } x T A \Longrightarrow P M$

$\bigwedge A B. M = \text{Pair } A B \Longrightarrow P M$

$\bigwedge A. M = \text{Fst } A \Longrightarrow P M$

$\bigwedge A. M = \text{Snd } A \Longrightarrow P M$

shows $P M$

using *assms* **by**(*induction rule: trm-induct, auto*)

lemma *trm-depth-induct*:

assumes

$P \text{Unit}$

$\wedge x. P (Var x)$
 $\wedge A B. \llbracket \wedge K. depth K < depth (App A B) \implies P K \rrbracket \implies P (App A B)$
 $\wedge M x T A. (\wedge K. depth K < depth (Fn x T A) \implies P K) \implies P (Fn x T A)$
 $\wedge A B. \llbracket \wedge K. depth K < depth (Pair A B) \implies P K \rrbracket \implies P (Pair A B)$
 $\wedge A. \llbracket \wedge K. depth K < depth (Fst A) \implies P K \rrbracket \implies P (Fst A)$
 $\wedge A. \llbracket \wedge K. depth K < depth (Snd A) \implies P K \rrbracket \implies P (Snd A)$
shows $P M$
proof(*induction depth M arbitrary: M rule: less-induct*)
fix $M :: 'a trm$
assume $IH: depth K < depth M \implies P K$ **for** K
hence
 $M = Unit \implies P M$
 $\wedge x. M = Var x \implies P M$
 $\wedge A B. M = App A B \implies P M$
 $\wedge x T A. M = Fn x T A \implies P M$
 $\wedge A B. M = Pair A B \implies P M$
 $\wedge A. M = Fst A \implies P M$
 $\wedge A. M = Snd A \implies P M$
using *assms* **by** *blast+*
thus $P M$ **using** *trm-cases*[**where** $M=M$] **by** *blast*
qed

context *fresh* **begin**

lemma *fresh-fn*:
fixes $x :: 'a$ **and** $S :: 'a set$
assumes *finite S*
shows $\exists y B. y \notin S \wedge B = [y \leftrightarrow x] \cdot A \wedge (Fn x T A = Fn y T B)$
proof –
have $*$: *finite* ($\{x\} \cup fvs A \cup S$) **using** *fvs-finite assms* **by** *auto*
obtain y **where** $y = fresh-in (\{x\} \cup fvs A \cup S)$ **by** *auto*
hence $y \notin (\{x\} \cup fvs A \cup S)$ **using** *fresh-axioms* $*$ **unfolding** *class.fresh-def*
by *metis*
hence $y \neq x \wedge y \notin fvs A \wedge y \notin S$ **by** *auto*

obtain B **where** $B = [y \leftrightarrow x] \cdot A$ **by** *auto*
hence $Fn x T A = Fn y T B$ **using** *fn-eq* $\langle y \neq x \rangle \langle y \notin fvs A \rangle$ **by** *metis*
thus *?thesis* **using** $\langle y \neq x \rangle \langle y \notin S \rangle$ B **by** *metis*
qed

lemma *trm-strong-induct*:
fixes $P :: 'a set \Rightarrow 'a trm \Rightarrow bool$
assumes
 $P S Unit$
 $\wedge x. P S (Var x)$
 $\wedge A B. \llbracket P S A; P S B \rrbracket \implies P S (App A B)$
 $\wedge x T. x \notin S \implies (\wedge A. P S A \implies P S (Fn x T A))$
 $\wedge A B. \llbracket P S A; P S B \rrbracket \implies P S (Pair A B)$
 $\wedge A. P S A \implies P S (Fst A)$

```

     $\bigwedge A. P S A \implies P S (Snd A)$ 
    finite S
  shows  $P S M$ 
proof -
  have  $\bigwedge \pi. P S (\pi \cdot M)$ 
proof (induction M rule: trm-induct)
  case 1
    thus ?case using assms(1) trm-prm-simp(1) by metis
  next
  case (2 x)
    thus ?case using assms(2) trm-prm-simp(2) by metis
  next
  case (3 A B)
    thus ?case using assms(3) trm-prm-simp(3) by metis
  next
  case (4 x T A)
    have finite S finite (fvs ( $\pi \cdot A$ )) finite  $\{\pi \$ x\}$ 
      using  $\langle \text{finite } S \rangle \text{ fvs-finite}$  by auto
    hence finite  $(S \cup \text{fvs } (\pi \cdot A) \cup \{\pi \$ x\})$  by auto

    obtain y where  $y = \text{fresh-in } (S \cup \text{fvs } (\pi \cdot A) \cup \{\pi \$ x\})$  by auto
    hence  $y \notin S \cup \text{fvs } (\pi \cdot A) \cup \{\pi \$ x\}$  using fresh-axioms unfolding
class.fresh-def
    using  $\langle \text{finite } (S \cup \text{fvs } (\pi \cdot A) \cup \{\pi \$ x\}) \rangle$  by metis
    hence  $y \neq \pi \$ x \ y \notin \text{fvs } (\pi \cdot A) \ y \notin S$  by auto
    hence *:  $\bigwedge A. P S A \implies P S (Fn y T A)$  using assms(4) by metis

    have  $P S (([y \leftrightarrow \pi \$ x] \diamond \pi) \cdot A)$  using 4 by metis
    hence  $P S (Fn y T (([y \leftrightarrow \pi \$ x] \diamond \pi) \cdot A))$  using * by metis
    moreover have  $(Fn y T (([y \leftrightarrow \pi \$ x] \diamond \pi) \cdot A)) = Fn (\pi \$ x) T (\pi \cdot A)$ 
      using trm-prm-apply-compose fn-eq  $\langle y \neq \pi \$ x \rangle \langle y \notin \text{fvs } (\pi \cdot A) \rangle$  by metis
    ultimately show ?case using trm-prm-simp(4) by metis
  next
  case (5 A B)
    thus ?case using assms(5) trm-prm-simp(5) by metis
  next
  case (6 A)
    thus ?case using assms(6) trm-prm-simp(6) by metis
  next
  case (7 A)
    thus ?case using assms(7) trm-prm-simp(7) by metis
  next
qed
  hence  $P S (\varepsilon \cdot M)$  by metis
  thus  $P S M$  using trm-prm-apply-id by metis
qed

```

lemma *trm-strong-cases*:

```
fixes P :: 'a set  $\Rightarrow$  'a trm  $\Rightarrow$  bool
```

assumes

$M = \text{Unit} \implies P S M$
 $\bigwedge x. M = \text{Var } x \implies P S M$
 $\bigwedge A B. M = \text{App } A B \implies P S M$
 $\bigwedge x T A. M = \text{Fn } x T A \implies x \notin S \implies P S M$
 $\bigwedge A B. M = \text{Pair } A B \implies P S M$
 $\bigwedge A. M = \text{Fst } A \implies P S M$
 $\bigwedge A. M = \text{Snd } A \implies P S M$
finite S

shows $P S M$

using *assms* **by**(*induction S M rule: trm-strong-induct, metis+*)

lemma *trm-strong-depth-induct*:

fixes $P :: 'a \text{ set} \Rightarrow 'a \text{ trm} \Rightarrow \text{bool}$

assumes

$P S \text{Unit}$
 $\bigwedge x. P S (\text{Var } x)$
 $\bigwedge A B. [\bigwedge K. \text{depth } K < \text{depth } (\text{App } A B) \implies P S K] \implies P S (\text{App } A B)$
 $\bigwedge x T. x \notin S \implies (\bigwedge A. (\bigwedge K. \text{depth } K < \text{depth } (\text{Fn } x T A) \implies P S K) \implies P S (\text{Fn } x T A))$
 $\bigwedge A B. [\bigwedge K. \text{depth } K < \text{depth } (\text{Pair } A B) \implies P S K] \implies P S (\text{Pair } A B)$
 $\bigwedge A. [\bigwedge K. \text{depth } K < \text{depth } (\text{Fst } A) \implies P S K] \implies P S (\text{Fst } A)$
 $\bigwedge A. [\bigwedge K. \text{depth } K < \text{depth } (\text{Snd } A) \implies P S K] \implies P S (\text{Snd } A)$
finite S

shows $P S M$

proof(*induction depth M arbitrary: M rule: less-induct*)

fix $M :: 'a \text{ trm}$

assume *IH*: $\text{depth } K < \text{depth } M \implies P S K$ **for** K

hence

$M = \text{Unit} \implies P S M$
 $\bigwedge x. M = \text{Var } x \implies P S M$
 $\bigwedge A B. M = \text{App } A B \implies P S M$
 $\bigwedge x T A. M = \text{Fn } x T A \implies x \notin S \implies P S M$
 $\bigwedge A B. M = \text{Pair } A B \implies P S M$
 $\bigwedge A. M = \text{Fst } A \implies P S M$
 $\bigwedge A. M = \text{Snd } A \implies P S M$
finite S

using *assms IH* **by** *metis+*

thus $P S M$ **using** *trm-strong-cases*[**where** $M=M$] **by** *blast*

qed

lemma *trm-prm-fvs*:

shows $\text{fvs } (\pi \cdot M) = \pi \{ \$ \} \text{fvs } M$

by(*transfer, metis ptrm-prm-fvs*)

inductive *typing* :: $'a \text{ typing-ctx} \Rightarrow 'a \text{ trm} \Rightarrow \text{type} \Rightarrow \text{bool}$ ($- \vdash - : -$) **where**

tunit: $\Gamma \vdash \text{Unit} : T\text{Unit}$

| *tvar*: $\Gamma x = \text{Some } \tau \implies \Gamma \vdash \text{Var } x : \tau$

| *tapp*: $[\Gamma \vdash f : (T\text{Arr } \tau \sigma); \Gamma \vdash x : \tau] \implies \Gamma \vdash \text{App } f x : \sigma$

| *tfn*: $\Gamma(x \mapsto \tau) \vdash A : \sigma \implies \Gamma \vdash \text{Fn } x \tau A : (\text{TArr } \tau \sigma)$
| *tpair*: $\llbracket \Gamma \vdash A : \tau; \Gamma \vdash B : \sigma \rrbracket \implies \Gamma \vdash \text{Pair } A B : (\text{TPair } \tau \sigma)$
| *tfst*: $\Gamma \vdash P : (\text{TPair } \tau \sigma) \implies \Gamma \vdash \text{Fst } P : \tau$
| *tsnd*: $\Gamma \vdash P : (\text{TPair } \tau \sigma) \implies \Gamma \vdash \text{Snd } P : \sigma$

lemma *typing-prm*:

assumes $\Gamma \vdash M : \tau \wedge y. y \in \text{fvs } M \implies \Gamma y = \Delta (\pi \$ y)$

shows $\Delta \vdash \pi \cdot M : \tau$

using *assms* **proof**(*induction arbitrary*: Δ *rule*: *typing.induct*)

case (*tunit* Γ)

thus *?case* **using** *typing.tunit trm-prm-simp(1)* **by** *metis*

next

case (*tvar* $\Gamma x \tau$)

thus *?case* **using** *typing.tvar trm-prm-simp(2) fvs-simp(2) singletonI* **by** *metis*

next

case (*tapp* $\Gamma A \tau \sigma B$)

thus *?case* **using** *typing.tapp trm-prm-simp(3) fvs-simp(3) UnCI* **by** *metis*

next

case (*tfn* $\Gamma x \tau A \sigma$)

have $y \in \text{fvs } A \implies (\Gamma(x \mapsto \tau)) y = (\Delta(\pi \$ x \mapsto \tau)) (\pi \$ y)$ **for** y

proof(*cases* $y = x$)

case *True*

thus *?thesis* **using** *fun-upd-apply* **by** *simp*

next

case *False*

assume $y \in \text{fvs } A$

hence $y \in \text{fvs } (\text{Fn } x \tau A)$ **using** *fvs-simp(4)* $\langle y \neq x \rangle$ *DiffI singletonD* **by**

fastforce

hence $\Gamma y = \Delta (\pi \$ y)$ **using** *tfn.prem*s **by** *metis*

thus *?thesis* **by** (*simp add*: *prm-apply-unequal*)

next

qed

hence $\Delta(\pi \$ x \mapsto \tau) \vdash \pi \cdot A : \sigma$ **using** *tfn.IH* **by** *metis*

thus *?case* **using** *trm-prm-simp(4) typing.tfn* **by** *metis*

next

case (*tpair* $\Gamma A B$)

thus *?case* **using** *typing.tpair trm-prm-simp(5) fvs-simp(5) UnCI* **by** *metis*

next

case (*tfst* $\Gamma P \tau \sigma$)

thus *?case* **using** *typing.tfst trm-prm-simp(6) fvs-simp(6)* **by** *metis*

next

case (*tsnd* $\Gamma P \tau \sigma$)

thus *?case* **using** *typing.tsnd trm-prm-simp(7) fvs-simp(7)* **by** *metis*

next

qed

lemma *typing-swp*:

assumes $\Gamma(a \mapsto \sigma) \vdash M : \tau \ b \notin \text{fvs } M$

shows $\Gamma(b \mapsto \sigma) \vdash [a \leftrightarrow b] \cdot M : \tau$

```

proof –
  have  $y \in fvs\ M \implies (\Gamma(a \mapsto \sigma))\ y = (\Gamma(b \mapsto \sigma))\ ([a \leftrightarrow b]\ \$\ y)$  for  $y$ 
  proof –
    assume  $y \in fvs\ M$ 
    hence  $y \neq b$  using assms(2) by auto
    consider  $y = a \mid y \neq a$  by auto
    thus  $(\Gamma(a \mapsto \sigma))\ y = (\Gamma(b \mapsto \sigma))\ ([a \leftrightarrow b]\ \$\ y)$ 
    by(cases, simp add: prm-unit-action, simp add: prm-unit-inaction  $\langle y \neq b \rangle$ )
  qed
  thus ?thesis using typing-prm assms(1) by metis
qed

lemma typing-unitE:
  assumes  $\Gamma \vdash Unit : \tau$ 
  shows  $\tau = TUnit$ 
using assms
  apply cases
  apply blast
  apply (auto simp add: unit-not-var unit-not-app unit-not-fn unit-not-pair unit-not-fst
unit-not-snd)
done

lemma typing-varE:
  assumes  $\Gamma \vdash Var\ x : \tau$ 
  shows  $\Gamma\ x = Some\ \tau$ 
using assms
  apply cases
  prefer 2
  apply (metis trm-simp(1))
  apply (metis unit-not-var)
  apply (auto simp add: var-not-app var-not-fn var-not-pair var-not-fst var-not-snd)
done

lemma typing-appE:
  assumes  $\Gamma \vdash App\ A\ B : \sigma$ 
  shows  $\exists \tau. (\Gamma \vdash A : (TArr\ \tau\ \sigma)) \wedge (\Gamma \vdash B : \tau)$ 
using assms
  apply cases
  prefer 3
  apply (metis trm-simp(2, 3))
  apply (metis unit-not-app)
  apply (metis var-not-app)
  apply (auto simp add: app-not-fn app-not-pair app-not-fst app-not-snd)
done

lemma typing-fnE:
  assumes  $\Gamma \vdash Fn\ x\ T\ A : \vartheta$ 
  shows  $\exists \sigma. \vartheta = (TArr\ T\ \sigma) \wedge (\Gamma(x \mapsto T) \vdash A : \sigma)$ 
using assms proof(cases)

```

```

case (tfn y S B σ)
  from this consider
     $x = y \wedge T = S \wedge A = B \mid x \neq y \wedge T = S \wedge x \notin \text{fvs } B \wedge A = [x \leftrightarrow y] \cdot B$ 
    using trm-simp(4) by metis
  thus ?thesis proof(cases)
    case 1
      thus ?thesis using tfn by metis
    next
      case 2
        thus ?thesis using tfn typing-swp prm-unit-commutes by metis
      next
        qed
    next
      qed (
        metis unit-not-fn,
        metis var-not-fn,
        metis app-not-fn,
        metis fn-not-pair,
        metis fn-not-fst,
        metis fn-not-snd
      )

```

```

lemma typing-pairE:
  assumes  $\Gamma \vdash \text{Pair } A \ B : \vartheta$ 
  shows  $\exists \tau \ \sigma. \vartheta = (\text{TPair } \tau \ \sigma) \wedge (\Gamma \vdash A : \tau) \wedge (\Gamma \vdash B : \sigma)$ 
using assms proof(cases)
  case (tpair A τ B σ)
    thus ?thesis using trm-simp(5) trm-simp(6) by blast
  next
    qed (
      metis unit-not-pair,
      metis var-not-pair,
      metis app-not-pair,
      metis fn-not-pair,
      metis pair-not-fst,
      metis pair-not-snd
    )

```

```

lemma typing-fstE:
  assumes  $\Gamma \vdash \text{Fst } P : \tau$ 
  shows  $\exists \sigma. (\Gamma \vdash P : (\text{TPair } \tau \ \sigma))$ 
using assms proof(cases)
  case (tfst P σ)
    thus ?thesis using trm-simp(7) by blast
  next
    qed (
      metis unit-not-fst,
      metis var-not-fst,
      metis app-not-fst,
    )

```

metis fn-not-fst,
metis pair-not-fst,
metis fst-not-snd
)

lemma *typing-sndE*:
assumes $\Gamma \vdash \text{Snd } P : \sigma$
shows $\exists \tau. (\Gamma \vdash P : (\text{TPair } \tau \sigma))$
using *assms* **proof**(*cases*)
case (*tsnd* $P \sigma$)
thus ?thesis **using** *trm-simp*(8) **by** *blast*
next
qed (
metis *unit-not-snd*,
metis *var-not-snd*,
metis *app-not-snd*,
metis *fn-not-snd*,
metis *pair-not-snd*,
metis *fst-not-snd*
)

theorem *typing-weaken*:
assumes $\Gamma \vdash M : \tau \ y \notin \text{fvs } M$
shows $\Gamma(y \mapsto \sigma) \vdash M : \tau$
using *assms* **proof**(*induction rule: typing.induct*)
case (*tunit* Γ)
thus ?case **using** *typing.tunit* **by** *metis*
next
case (*tvar* $\Gamma x \tau$)
hence $y \neq x$ **using** *fvs-simp*(2) *singletonI* **by** *force*
hence $(\Gamma(y \mapsto \sigma)) \ x = \text{Some } \tau$ **using** *tvar.hyps* *fun-upd-apply* **by** *simp*
thus ?case **using** *typing.tvar* **by** *metis*
next
case (*tapp* $\Gamma f \tau \tau' x$)
from $\langle y \notin \text{fvs } (\text{App } f x) \rangle$ **have** $y \notin \text{fvs } f \ y \notin \text{fvs } x$ **using** *fvs-simp*(3) *Un-iff* **by**
force+
hence $\Gamma(y \mapsto \sigma) \vdash f : (\text{TArr } \tau \tau')$ $\Gamma(y \mapsto \sigma) \vdash x : \tau$ **using** *tapp.IH* **by** *metis+*
thus ?case **using** *typing.tapp* **by** *metis*
next
case (*tfn* $\Gamma x \tau A \tau'$)
from $\langle y \notin \text{fvs } (\text{Fn } x \tau A) \rangle$ **consider** $y = x \mid y \neq x \wedge y \notin \text{fvs } A$
using *fvs-simp*(4) *DiffI* *empty-iff* *insert-iff* **by** *fastforce*
thus ?case **proof**(*cases*)
case 1
hence $(\Gamma(y \mapsto \sigma, x \mapsto \tau)) \vdash A : \tau'$ **using** *tfn.hyps* *fun-upd-upd* **by** *simp*
thus ?thesis **using** *typing.tfn* **by** *metis*
next
case 2
hence $y \neq x \ y \notin \text{fvs } A$ **by** *auto*

```

    hence  $\Gamma(x \mapsto \tau, y \mapsto \sigma) \vdash A : \tau'$  using tfn.IH by metis
    hence  $\Gamma(y \mapsto \sigma, x \mapsto \tau) \vdash A : \tau'$  using  $\langle y \neq x \rangle$  fun-upd-twist by metis
    thus ?thesis using typing.tfn by metis
  next
  qed
next
case (tpair  $\Gamma A \tau B \sigma$ )
  thus ?case using typing.tpair fvs-simp(5) UnCI by metis
next
case (tfst  $\Gamma P \tau \sigma$ )
  thus ?case using typing.tfst fvs-simp(6) by metis
next
case (tsnd  $\Gamma P \tau \sigma$ )
  thus ?case using typing.tsnd fvs-simp(7) by metis
next
qed

```

lift-definition *infer* :: 'a *typing-ctx* \Rightarrow 'a *trm* \Rightarrow *type option* is *ptrm-infer-type*
using *ptrm-infer-type-alpha-equiv*.

export-code *infer* *fresh-nat-inst.fresh-in-nat* in *Haskell*

lemma *infer-simp*:

shows

```

infer  $\Gamma$  Unit = Some TUnit
infer  $\Gamma$  (Var x) =  $\Gamma$  x
infer  $\Gamma$  (App A B) = (case (infer  $\Gamma$  A, infer  $\Gamma$  B) of
  (Some (TArr  $\tau \sigma$ ), Some  $\tau'$ )  $\Rightarrow$  (if  $\tau = \tau'$  then Some  $\sigma$  else None)
  | -  $\Rightarrow$  None
)
infer  $\Gamma$  (Fn x  $\tau$  A) = (case infer ( $\Gamma(x \mapsto \tau)$ ) A of
  Some  $\sigma \Rightarrow$  Some (TArr  $\tau \sigma$ )
  | None  $\Rightarrow$  None
)
infer  $\Gamma$  (Pair A B) = (case (infer  $\Gamma$  A, infer  $\Gamma$  B) of
  (Some  $\tau$ , Some  $\sigma$ )  $\Rightarrow$  Some (TPair  $\tau \sigma$ )
  | -  $\Rightarrow$  None
)
infer  $\Gamma$  (Fst P) = (case infer  $\Gamma$  P of
  (Some (TPair  $\tau \sigma$ ))  $\Rightarrow$  Some  $\tau$ 
  | -  $\Rightarrow$  None
)
infer  $\Gamma$  (Snd P) = (case infer  $\Gamma$  P of
  (Some (TPair  $\tau \sigma$ ))  $\Rightarrow$  Some  $\sigma$ 
  | -  $\Rightarrow$  None
)

```

by((*transfer*, *simp*) $+$)

```

lemma infer-unitE:
  assumes infer  $\Gamma$  Unit = Some  $\tau$ 
  shows  $\tau = TUnit$ 
using assms by(transfer, simp)

lemma infer-varE:
  assumes infer  $\Gamma$  (Var  $x$ ) = Some  $\tau$ 
  shows  $\Gamma$   $x$  = Some  $\tau$ 
using assms by(transfer, simp)

lemma infer-appE:
  assumes infer  $\Gamma$  (App  $A$   $B$ ) = Some  $\tau$ 
  shows  $\exists \sigma$ . infer  $\Gamma$   $A$  = Some (TArr  $\sigma$   $\tau$ )  $\wedge$  infer  $\Gamma$   $B$  = Some  $\sigma$ 
using assms proof(transfer)
  fix  $\Gamma$  :: 'a typing-ctx and  $A$   $B$   $\tau$ 
  assume  $H$ : ptrm-infer-type  $\Gamma$  (PApp  $A$   $B$ ) = Some  $\tau$ 

  have ptrm-infer-type  $\Gamma$   $A$   $\neq$  None
  proof(rule classical, auto)
    assume ptrm-infer-type  $\Gamma$   $A$  = None
    hence ptrm-infer-type  $\Gamma$  (PApp  $A$   $B$ ) = None by auto
    thus False using  $H$  by auto
  qed
  from this obtain  $T$  where *: ptrm-infer-type  $\Gamma$   $A$  = Some  $T$  by auto

  have  $T \neq TVar$   $x$  for  $x$ 
  proof(rule classical, auto)
    fix  $x$ 
    assume  $T = TVar$   $x$ 
    hence ptrm-infer-type  $\Gamma$   $A$  = Some (TVar  $x$ ) using * by metis
    hence ptrm-infer-type  $\Gamma$  (PApp  $A$   $B$ ) = None by simp
    thus False using  $H$  by auto
  qed
  moreover have  $T \neq TUnit$ 
  proof(rule classical, auto)
    fix  $x$ 
    assume  $T = TUnit$ 
    hence ptrm-infer-type  $\Gamma$   $A$  = Some TUnit using * by metis
    hence ptrm-infer-type  $\Gamma$  (PApp  $A$   $B$ ) = None by simp
    thus False using  $H$  by auto
  qed
  moreover have  $T \neq TPair$   $\tau$   $\sigma$  for  $\tau$   $\sigma$ 
  proof(rule classical, auto)
    fix  $\tau$   $\sigma$ 
    assume  $T = TPair$   $\tau$   $\sigma$ 
    hence ptrm-infer-type  $\Gamma$   $A$  = Some (TPair  $\tau$   $\sigma$ ) using * by metis
    hence ptrm-infer-type  $\Gamma$  (PApp  $A$   $B$ ) = None by simp
    thus False using  $H$  by auto
  qed

```

ultimately obtain $\sigma \tau'$ **where** $T = TArr \sigma \tau'$ **by** (*cases T, blast, auto*)
hence *: *ptrm-infer-type* $\Gamma A = Some (TArr \sigma \tau')$ **using** * **by** *metis*

have *ptrm-infer-type* $\Gamma B \neq None$
proof(*rule classical, auto*)
 assume *ptrm-infer-type* $\Gamma B = None$
 hence *ptrm-infer-type* $\Gamma (PApp A B) = None$ **using** * **by** *auto*
 thus *False* **using** *H* **by** *auto*
qed
from *this* **obtain** σ' **where** **: *ptrm-infer-type* $\Gamma B = Some \sigma'$ **by** *auto*

have $\sigma = \sigma'$
proof(*rule classical*)
 assume $\sigma \neq \sigma'$
 hence *ptrm-infer-type* $\Gamma (PApp A B) = None$ **using** * ** **by** *simp*
 hence *False* **using** *H* **by** *auto*
 thus $\sigma = \sigma'$ **by** *blast*
qed
hence **: *ptrm-infer-type* $\Gamma B = Some \sigma$ **using** ** **by** *auto*

have *ptrm-infer-type* $\Gamma (PApp A B) = Some \tau'$ **using** * ** **by** *auto*
hence $\tau = \tau'$ **using** *H* **by** *auto*
hence *: *ptrm-infer-type* $\Gamma A = Some (TArr \sigma \tau)$ **using** * **by** *auto*

show $\exists \sigma. \text{ptrm-infer-type } \Gamma A = Some (TArr \sigma \tau) \wedge \text{ptrm-infer-type } \Gamma B = Some \sigma$
 using * ** **by** *auto*
qed

lemma *infer-fnE*:
 assumes *infer* $\Gamma (Fn x T A) = Some \tau$
 shows $\exists \sigma. \tau = TArr T \sigma \wedge \text{infer } (\Gamma(x \mapsto T)) A = Some \sigma$
using *assms* **proof**(*transfer*)
 fix $x :: 'a$ **and** $\Gamma T A \tau$
 assume *H*: *ptrm-infer-type* $\Gamma (PFn x T A) = Some \tau$

have *ptrm-infer-type* $(\Gamma(x \mapsto T)) A \neq None$
proof(*rule classical, auto*)
 assume *ptrm-infer-type* $(\Gamma(x \mapsto T)) A = None$
 hence *ptrm-infer-type* $\Gamma (PFn x T A) = None$ **by** *auto*
 thus *False* **using** *H* **by** *auto*

qed
from *this* **obtain** σ **where** *: *ptrm-infer-type* $(\Gamma(x \mapsto T)) A = Some \sigma$ **by** *auto*

have *ptrm-infer-type* $\Gamma (PFn x T A) = Some (TArr T \sigma)$ **using** * **by** *auto*
hence $\tau = TArr T \sigma$ **using** *H* **by** *auto*
thus $\exists \sigma. \tau = TArr T \sigma \wedge \text{ptrm-infer-type } (\Gamma(x \mapsto T)) A = Some \sigma$
 using * **by** *auto*

qed

lemma *infer-pairE*:
assumes *infer* Γ (*Pair* A B) = *Some* τ
shows $\exists T S. \tau = TPair\ T\ S \wedge infer\ \Gamma\ A = Some\ T \wedge infer\ \Gamma\ B = Some\ S$
using *assms* **proof**(*transfer*)
fix $A\ B :: 'a\ ptrm$ **and** $\Gamma\ \tau$
assume $H: ptrm-infer-type\ \Gamma\ (PPair\ A\ B) = Some\ \tau$

have *ptrm-infer-type* $\Gamma\ A \neq None$
proof(*rule classical, auto*)
assume *ptrm-infer-type* $\Gamma\ A = None$
hence *ptrm-infer-type* $\Gamma\ (PPair\ A\ B) = None$ **by** *auto*
thus *False* **using** H **by** *auto*
qed

moreover **have** *ptrm-infer-type* $\Gamma\ B \neq None$
proof(*rule classical, auto*)
assume *ptrm-infer-type* $\Gamma\ B = None$
hence *ptrm-infer-type* $\Gamma\ (PPair\ A\ B) = None$ **by** (*simp add: option.case-eq-if*)
thus *False* **using** H **by** *auto*
qed

ultimately obtain $T\ S$
where $\tau = TPair\ T\ S$ *ptrm-infer-type* $\Gamma\ A = Some\ T$ *ptrm-infer-type* $\Gamma\ B = Some\ S$
using H **by** *auto*
thus $\exists T S. \tau = TPair\ T\ S \wedge ptrm-infer-type\ \Gamma\ A = Some\ T \wedge ptrm-infer-type\ \Gamma\ B = Some\ S$ **by** *auto*
qed

lemma *infer-fstE*:
assumes *infer* Γ (*Fst* P) = *Some* τ
shows $\exists T S. infer\ \Gamma\ P = Some\ (TPair\ T\ S) \wedge \tau = T$
using *assms* **proof**(*transfer*)
fix $P :: 'a\ ptrm$ **and** $\Gamma\ \tau$
assume $H: ptrm-infer-type\ \Gamma\ (PFst\ P) = Some\ \tau$

have *ptrm-infer-type* $\Gamma\ P \neq None$
proof(*rule classical, auto*)
assume *ptrm-infer-type* $\Gamma\ P = None$
thus *False* **using** H **by** *simp*
qed

moreover **have** *ptrm-infer-type* $\Gamma\ P \neq Some\ TUnit$
proof(*rule classical, auto*)
assume *ptrm-infer-type* $\Gamma\ P = Some\ TUnit$
thus *False* **using** H **by** *simp*
qed

moreover **have** *ptrm-infer-type* $\Gamma\ P \neq Some\ (TVar\ x)$ **for** x
proof(*rule classical, auto*)
assume *ptrm-infer-type* $\Gamma\ P = Some\ (TVar\ x)$
thus *False* **using** H **by** *simp*

```

qed
moreover have ptrm-infer-type  $\Gamma P \neq \text{Some } (TArr T S)$  for  $T S$ 
proof(rule classical, auto)
  assume ptrm-infer-type  $\Gamma P = \text{Some } (TArr T S)$ 
  thus False using  $H$  by simp
qed
ultimately obtain  $T S$  where
  ptrm-infer-type  $\Gamma P = \text{Some } (TPair T S)$ 
  using type.distinct type.exhaust option.exhaust by metis
moreover hence ptrm-infer-type  $\Gamma (PFst P) = \text{Some } T$  by simp
ultimately show  $\exists T S. \text{ptrm-infer-type } \Gamma P = \text{Some } (TPair T S) \wedge \tau = T$ 
  using  $H$  by auto
qed

lemma infer-sndE:
  assumes infer  $\Gamma (Snd P) = \text{Some } \tau$ 
  shows  $\exists T S. \text{infer } \Gamma P = \text{Some } (TPair T S) \wedge \tau = S$ 
using assms proof(transfer)
  fix  $P :: 'a \text{ ptrm}$  and  $\Gamma \tau$ 
  assume  $H: \text{ptrm-infer-type } \Gamma (PSnd P) = \text{Some } \tau$ 

  have ptrm-infer-type  $\Gamma P \neq \text{None}$ 
  proof(rule classical, auto)
    assume ptrm-infer-type  $\Gamma P = \text{None}$ 
    thus False using  $H$  by simp
  qed
  moreover have ptrm-infer-type  $\Gamma P \neq \text{Some } TUnit$ 
  proof(rule classical, auto)
    assume ptrm-infer-type  $\Gamma P = \text{Some } TUnit$ 
    thus False using  $H$  by simp
  qed
  moreover have ptrm-infer-type  $\Gamma P \neq \text{Some } (TVar x)$  for  $x$ 
  proof(rule classical, auto)
    assume ptrm-infer-type  $\Gamma P = \text{Some } (TVar x)$ 
    thus False using  $H$  by simp
  qed
  moreover have ptrm-infer-type  $\Gamma P \neq \text{Some } (TArr T S)$  for  $T S$ 
  proof(rule classical, auto)
    assume ptrm-infer-type  $\Gamma P = \text{Some } (TArr T S)$ 
    thus False using  $H$  by simp
  qed
  ultimately obtain  $T S$  where
    ptrm-infer-type  $\Gamma P = \text{Some } (TPair T S)$ 
    using type.distinct type.exhaust option.exhaust by metis
  moreover hence ptrm-infer-type  $\Gamma (PSnd P) = \text{Some } S$  by simp
  ultimately show  $\exists T S. \text{ptrm-infer-type } \Gamma P = \text{Some } (TPair T S) \wedge \tau = S$ 
    using  $H$  by auto
qed

```

lemma *infer-sound*:
assumes $\text{infer } \Gamma M = \text{Some } \tau$
shows $\Gamma \vdash M : \tau$
using *assms* **proof**(*induction M arbitrary: $\Gamma \tau$ rule: trm-induct*)
case 1
 thus ?case **using** *infer-unitE typing.tunit* **by** *metis*
next
case (2 x)
 hence $\Gamma x = \text{Some } \tau$ **using** *infer-varE* **by** *metis*
 thus ?case **using** *typing.tvar* **by** *metis*
next
case (3 $A B$)
 from $\langle \text{infer } \Gamma (\text{App } A B) = \text{Some } \tau \rangle$ **obtain** σ
 where $\text{infer } \Gamma A = \text{Some } (TArr \sigma \tau)$ **and** $\text{infer } \Gamma B = \text{Some } \sigma$
 using *infer-appE* **by** *metis*
 thus ?case **using** 3.IH *typing.tapp* **by** *metis*
next
case (4 $x T A \Gamma \tau$)
 from $\langle \text{infer } \Gamma (\text{Fn } x T A) = \text{Some } \tau \rangle$ **obtain** σ
 where $\tau = TArr T \sigma$ **and** $\text{infer } (\Gamma(x \mapsto T)) A = \text{Some } \sigma$
 using *infer-fnE* **by** *metis*
 thus ?case **using** 4.IH *typing.tfn* **by** *metis*
next
case (5 $A B \Gamma \tau$)
 thus ?case **using** *typing.tpair infer-pairE* **by** *metis*
next
case (6 $P \Gamma \tau$)
 thus ?case **using** *typing.tfst infer-fstE* **by** *metis*
next
case (7 $P \Gamma \tau$)
 thus ?case **using** *typing.tsnd infer-sndE* **by** *metis*
next
qed

lemma *infer-complete*:
assumes $\Gamma \vdash M : \tau$
shows $\text{infer } \Gamma M = \text{Some } \tau$
using *assms* **proof**(*induction*)
case (*tfn* $\Gamma x \tau A \sigma$)
 thus ?case **by** (*simp add: infer-simp(4) tfn.IH*)
next
qed (*auto simp add: infer-simp*)

theorem *infer-valid*:
shows $(\Gamma \vdash M : \tau) = (\text{infer } \Gamma M = \text{Some } \tau)$
using *infer-sound infer-complete* **by** *blast*

inductive *substitutes* :: ' $a \text{ trm} \Rightarrow 'a \Rightarrow 'a \text{ trm} \Rightarrow 'a \text{ trm} \Rightarrow \text{bool}$ **where**
 unit: substitutes Unit y M Unit

| *var1*: $x = y \implies \text{substitutes } (\text{Var } x) y M M$
| *var2*: $x \neq y \implies \text{substitutes } (\text{Var } x) y M (\text{Var } x)$
| *app*: $\llbracket \text{substitutes } A x M A'; \text{substitutes } B x M B' \rrbracket \implies \text{substitutes } (\text{App } A B) x M (\text{App } A' B')$
| *fn*: $\llbracket x \neq y; y \notin \text{fvs } M; \text{substitutes } A x M A' \rrbracket \implies \text{substitutes } (\text{Fn } y T A) x M (\text{Fn } y T A')$
| *pair*: $\llbracket \text{substitutes } A x M A'; \text{substitutes } B x M B' \rrbracket \implies \text{substitutes } (\text{Pair } A B) x M (\text{Pair } A' B')$
| *fst*: $\text{substitutes } P x M P' \implies \text{substitutes } (\text{Fst } P) x M (\text{Fst } P')$
| *snd*: $\text{substitutes } P x M P' \implies \text{substitutes } (\text{Snd } P) x M (\text{Snd } P')$

lemma *substitutes-prm*:

assumes *substitutes* $A x M A'$
shows *substitutes* $(\pi \cdot A) (\pi \$ x) (\pi \cdot M) (\pi \cdot A')$
using *assms* **proof**(*induction*)
 case (*unit* $y M$)
 thus ?*case* **using** *substitutes.unit trm-prm-simp(1)* **by** *metis*
 case (*var1* $x y M$)
 thus ?*case* **using** *substitutes.var1 trm-prm-simp(2)* **by** *metis*
 next
 case (*var2* $x y M$)
 thus ?*case* **using** *substitutes.var2 trm-prm-simp(2) prm-apply-unequal* **by** *metis*
 next
 case (*app* $A x M A' B B'$)
 thus ?*case* **using** *substitutes.app trm-prm-simp(3)* **by** *metis*
 next
 case (*fn* $x y M A A' T$)
 thus ?*case*
 using *substitutes.fn trm-prm-simp(4) prm-apply-unequal prm-set-notmembership*
trm-prm-fvs
 by *metis*
 next
 case (*pair* $A x M A' B B'$)
 thus ?*case* **using** *substitutes.pair trm-prm-simp(5)* **by** *metis*
 next
 case (*fst* $P x M P'$)
 thus ?*case* **using** *substitutes.fst trm-prm-simp(6)* **by** *metis*
 next
 case (*snd* $P x M P'$)
 thus ?*case* **using** *substitutes.snd trm-prm-simp(7)* **by** *metis*
 next
qed

lemma *substitutes-fvs*:

assumes *substitutes* $A x M A'$
shows $\text{fvs } A' \subseteq \text{fvs } A - \{x\} \cup \text{fvs } M$
using *assms* **proof**(*induction*)
 case (*unit* $y M$)
 thus ?*case* **using** *fvs-simp(1)* **by** *auto*

```

case (var1 x y M)
  thus ?case by auto
next
case (var2 x y M)
  thus ?case
    using fvs-simp(2) Un-subset-iff Un-upper2 insert-Diff-if insert-is-Un single-
tonD sup-commute
    by metis
next
case (app A x M A' B B')
  hence  $fvs\ A' \cup fvs\ B' \subseteq (fvs\ A - \{x\} \cup fvs\ M) \cup (fvs\ B - \{x\} \cup fvs\ M)$  by
auto
  hence  $fvs\ A' \cup fvs\ B' \subseteq (fvs\ A \cup fvs\ B) - \{x\} \cup fvs\ M$  by auto
  thus ?case using fvs-simp(3) by metis
next
case (fn x y M A A' T)
  hence  $fvs\ A' - \{y\} \subseteq fvs\ A - \{y\} - \{x\} \cup fvs\ M$  by auto
  thus ?case using fvs-simp(4) by metis
next
case (pair A x M A' B B')
  hence  $fvs\ A' \cup fvs\ B' \subseteq (fvs\ A - \{x\} \cup fvs\ M) \cup (fvs\ B - \{x\} \cup fvs\ M)$  by
auto
  hence  $fvs\ A' \cup fvs\ B' \subseteq (fvs\ A \cup fvs\ B) - \{x\} \cup fvs\ M$  by auto
  thus ?case using fvs-simp(5) by metis
next
case (fst P x M P')
  thus ?case using fvs-simp(6) by fastforce
next
case (snd P x M P')
  thus ?case using fvs-simp(7) by fastforce
next
qed

```

inductive-cases *substitutes-unitE'*: *substitutes Unit y M X*

lemma *substitutes-unitE*:

assumes *substitutes Unit y M X*

shows $X = Unit$

by(

rule *substitutes-unitE'*[**where** $y=y$ **and** $M=M$ **and** $X=X$],

metis *assms*,

auto *simp* *add: unit-not-var unit-not-app unit-not-fn unit-not-pair unit-not-fst*
unit-not-snd

)

inductive-cases *substitutes-varE'*: *substitutes (Var x) y M X*

lemma *substitutes-varE*:

assumes *substitutes (Var x) y M X*

shows $(x = y \wedge M = X) \vee (x \neq y \wedge X = Var\ x)$

by(

rule substitutes-varE'[**where** $x=x$ **and** $y=y$ **and** $M=M$ **and** $X=X$],
metis assms,
metis unit-not-var,
metis trm-simp(1),
metis trm-simp(1),
auto simp add: var-not-app var-not-fn var-not-pair var-not-fst var-not-snd
)

inductive-cases *substitutes-appE'*: *substitutes* (App A B) x M X

lemma *substitutes-appE*:

assumes *substitutes* (App A B) x M X

shows $\exists A' B'. \text{substitutes } A \ x \ M \ A' \wedge \text{substitutes } B \ x \ M \ B' \wedge X = \text{App } A' \ B'$

by(

cases rule: substitutes-appE'[**where** $A=A$ **and** $B=B$ **and** $x=x$ **and** $M=M$ **and** $X=X$],

metis assms,

metis unit-not-app,

metis var-not-app,

metis var-not-app,

metis trm-simp(2,3),

auto simp add: app-not-fn app-not-pair app-not-fst app-not-snd

)

inductive-cases *substitutes-fnE'*: *substitutes* (Fn y T A) x M X

lemma *substitutes-fnE*:

assumes *substitutes* (Fn y T A) x M X $y \neq x \ y \notin \text{fvs } M$

shows $\exists A'. \text{substitutes } A \ x \ M \ A' \wedge X = \text{Fn } y \ T \ A'$

using *assms proof*(*induction rule: substitutes-fnE'*[**where** $y=y$ **and** $T=T$ **and** $A=A$ **and** $x=x$ **and** $M=M$ **and** $X=X$])

case (6 z B B' S)

consider $y = z \wedge T = S \wedge A = B \mid y \neq z \wedge T = S \wedge y \notin \text{fvs } B \wedge A = [y \leftrightarrow z] \cdot B$

using $\langle \text{Fn } y \ T \ A = \text{Fn } z \ S \ B \rangle$ *trm-simp(4)* **by** *metis*

thus *?case proof*(*cases*)

case 1

thus *?thesis using 6* **by** *metis*

next

case 2

hence $y \neq z \ T = S \ y \notin \text{fvs } B \ A = [y \leftrightarrow z] \cdot B$ **by** *auto*

have *substitutes* ($[y \leftrightarrow z] \cdot B$) ($[y \leftrightarrow z] \ \$ \ x$) ($[y \leftrightarrow z] \cdot M$) ($[y \leftrightarrow z] \cdot B'$)

using *substitutes-prm* $\langle \text{substitutes } B \ x \ M \ B' \rangle$ **by** *metis*

hence *substitutes* A ($[y \leftrightarrow z] \ \$ \ x$) ($[y \leftrightarrow z] \cdot M$) ($[y \leftrightarrow z] \cdot B'$)

using $\langle A = [y \leftrightarrow z] \cdot B \rangle$ **by** *metis*

hence *substitutes* A x ($[y \leftrightarrow z] \cdot M$) ($[y \leftrightarrow z] \cdot B'$)

using $\langle y \neq x \rangle \langle x \neq z \rangle$ *prm-unit-inaction* **by** *metis*

hence *: *substitutes* A x M ($[y \leftrightarrow z] \cdot B'$)

using $\langle y \notin \text{fvs } M \rangle \langle z \notin \text{fvs } M \rangle$ *trm-prm-unit-inaction* **by** *metis*

have $y \notin \text{fvs } B'$

```

using
  substitutes-fvs ⟨substitutes B x M B'⟩ ⟨y ∉ fvs B⟩ ⟨y ∉ fvs M⟩
  Diff-subset UnE rev-subsetD
by blast
hence X = Fn y T ([y ↔ z] · B')
using ⟨X = Fn z S B'⟩ ⟨y ≠ z⟩ ⟨T = S⟩ fn-eq
by metis

thus ?thesis using * by auto
next
qed
next
qed (
  metis assms(1),
  metis unit-not-fn,
  metis var-not-fn,
  metis var-not-fn,
  metis app-not-fn,
  metis fn-not-pair,
  metis fn-not-fst,
  metis fn-not-snd
)

inductive-cases substitutes-pairE': substitutes (Pair A B) x M X
lemma substitutes-pairE:
  assumes substitutes (Pair A B) x M X
  shows ∃ A' B'. substitutes A x M A' ∧ substitutes B x M B' ∧ X = Pair A' B'
proof(cases rule: substitutes-pairE'[where A=A and B=B and x=x and M=M
and X=X])
  case (7 A A' B B')
    thus ?thesis using trm-simp(5) trm-simp(6) by blast
  next
qed (
  metis assms,
  metis unit-not-pair,
  metis var-not-pair,
  metis var-not-pair,
  metis app-not-pair,
  metis fn-not-pair,
  metis pair-not-fst,
  metis pair-not-snd
)

inductive-cases substitutes-fstE': substitutes (Fst P) x M X
lemma substitutes-fstE:
  assumes substitutes (Fst P) x M X
  shows ∃ P'. substitutes P x M P' ∧ X = Fst P'
proof(cases rule: substitutes-fstE'[where P=P and x=x and M=M and X=X])
  case (8 P P')

```

```

    thus ?thesis using trm-simp(7) by blast
  next
qed (
  metis assms,
  metis unit-not-fst,
  metis var-not-fst,
  metis var-not-fst,
  metis app-not-fst,
  metis fn-not-fst,
  metis pair-not-fst,
  metis fst-not-snd
)

inductive-cases substitutes-sndE': substitutes (Snd P) x M X
lemma substitutes-sndE:
  assumes substitutes (Snd P) x M X
  shows  $\exists P'. \text{substitutes } P \ x \ M \ P' \wedge X = \text{Snd } P'$ 
proof(cases rule: substitutes-sndE'[where P=P and x=x and M=M and X=X])
  case (9 P P')
    thus ?thesis using trm-simp(8) by blast
  next
qed (
  metis assms,
  metis unit-not-snd,
  metis var-not-snd,
  metis var-not-snd,
  metis app-not-snd,
  metis fn-not-snd,
  metis pair-not-snd,
  metis fst-not-snd
)

lemma substitutes-total:
  shows  $\exists X. \text{substitutes } A \ x \ M \ X$ 
proof(induction A rule: trm-strong-induct[where S={x}  $\cup$  fvs M])
  show finite ({x}  $\cup$  fvs M) using fvs-finite by auto
  next

  case 1
    obtain X :: 'a trm where X = Unit by auto
    thus ?case using substitutes.unit by metis
  next
  case (2 y)
    consider x = y | x  $\neq$  y by auto
    thus ?case proof(cases)
      case 1
        obtain X where X = M by auto
        hence substitutes (Var y) x M X using  $\langle x = y \rangle$  substitutes.var1 by metis
        thus ?thesis by auto

```

```

next
case 2
  obtain X where X = (Var y) by auto
  hence substitutes (Var y) x M X using ⟨x ≠ y⟩ substitutes.var2 by metis
  thus ?thesis by auto
next
qed
next
case (3 A B)
  from this obtain A' B' where A': substitutes A x M A' and B': substitutes B
x M B' by auto
  obtain X where X = App A' B' by auto
  hence substitutes (App A B) x M X using A' B' substitutes.app by metis
  thus ?case by auto
next
case (4 y T A)
  from this obtain A' where A': substitutes A x M A' by auto
  from ⟨y ∉ ({x} ∪ fvs M)⟩ have y ≠ x y ∉ fvs M by auto
  obtain X where X = Fn y T A' by auto
  hence substitutes (Fn y T A) x M X using substitutes.fn ⟨y ≠ x⟩ ⟨y ∉ fvs M⟩
A' by metis
  thus ?case by auto
next
case (5 A B)
  from this obtain A' B' where substitutes A x M A' substitutes B x M B' by
auto
  from this obtain X where X = Pair A' B' by auto
  hence substitutes (Pair A B) x M X
  using substitutes.pair ⟨substitutes A x M A'⟩ ⟨substitutes B x M B'⟩
  by metis
  thus ?case by auto
next
case (6 P)
  from this obtain P' where substitutes P x M P' by auto
  from this obtain X where X = Fst P' by auto
  hence substitutes (Fst P) x M X using substitutes.fst ⟨substitutes P x M P'⟩
by metis
  thus ?case by auto
next
case (7 P)
  from this obtain P' where substitutes P x M P' by auto
  from this obtain X where X = Snd P' by auto
  hence substitutes (Snd P) x M X using substitutes.snd ⟨substitutes P x M P'⟩
by metis
  thus ?case by auto
next
qed

```

lemma *substitutes-unique*:

```

assumes substitutes A x M B substitutes A x M C
shows  $B = C$ 
using assms proof(induction A arbitrary: B C rule: trm-strong-induct[where
 $S = \{x\} \cup \text{fvs } M$ ])
show finite ( $\{x\} \cup \text{fvs } M$ ) using fvs-finite by auto
next

case 1
  thus ?case using substitutes-unitE by metis
next
case (2 y)
  thus ?case using substitutes-varE by metis
next
case (3 X Y)
  thus ?case using substitutes-appE by metis
next
case (4 y T A)
  hence  $y \neq x$  and  $y \notin \text{fvs } M$  by auto
  thus ?case using 4 substitutes-fnE by metis
next
case (5 A B C D)
  thus ?case using substitutes-pairE by metis
next
case (6 P Q R)
  thus ?case using substitutes-fstE by metis
next
case (7 P Q R)
  thus ?case using substitutes-sndE by metis
next
qed

```

```

lemma substitutes-function:
shows  $\exists! X. \text{substitutes } A \ x \ M \ X$ 
using substitutes-total substitutes-unique by metis

```

```

definition subst :: 'a trm  $\Rightarrow$  'a  $\Rightarrow$  'a trm  $\Rightarrow$  'a trm ( $[-] ::= [-]$ ) where
  subst A x M  $\equiv$  (THE X. substitutes A x M X)

```

```

lemma subst-simp-unit:
shows  $\text{Unit}[x ::= M] = \text{Unit}$ 
unfolding subst-def by(rule, metis substitutes.unit, metis substitutes-function substitutes.unit)

```

```

lemma subst-simp-var1:
shows  $(\text{Var } x)[x ::= M] = M$ 
unfolding subst-def by(rule, metis substitutes.var1, metis substitutes-function substitutes.var1)

```

```

lemma subst-simp-var2:

```

```

assumes  $x \neq y$ 
shows  $(\text{Var } x)[y ::= M] = \text{Var } x$ 
unfolding subst-def by(
  rule,
  metis substitutes.var2 assms,
  metis substitutes-function substitutes.var2 assms
)

```

```

lemma subst-simp-app:
shows  $(\text{App } A B)[x ::= M] = \text{App } (A[x ::= M]) (B[x ::= M])$ 
unfolding subst-def proof
obtain  $A' B'$  where  $A': A' = (A[x ::= M])$  and  $B': B' = (B[x ::= M])$  by auto
hence substitutes  $A x M A'$  substitutes  $B x M B'$ 
unfolding subst-def
using substitutes-function theI by metis+
hence substitutes  $(\text{App } A B) x M (\text{App } A' B')$  using substitutes.app by metis
thus  $*$ : substitutes  $(\text{App } A B) x M (\text{App } (\text{THE } X. \text{substitutes } A x M X) (\text{THE } X. \text{substitutes } B x M X))$ 
using  $A' B'$  unfolding subst-def by metis

```

```

fix  $X$ 
assume substitutes  $(\text{App } A B) x M X$ 
thus  $X = \text{App } (\text{THE } X. \text{substitutes } A x M X) (\text{THE } X. \text{substitutes } B x M X)$ 
using substitutes-function * by metis
qed

```

```

lemma subst-simp-fn:
assumes  $x \neq y$   $y \notin \text{fvs } M$ 
shows  $(\text{Fn } y T A)[x ::= M] = \text{Fn } y T (A[x ::= M])$ 
unfolding subst-def proof
obtain  $A'$  where  $A': A' = (A[x ::= M])$  by auto
hence substitutes  $A x M A'$  unfolding subst-def using substitutes-function theI
by metis
hence substitutes  $(\text{Fn } y T A) x M (\text{Fn } y T A')$  using substitutes.fn assms by
metis
thus  $*$ : substitutes  $(\text{Fn } y T A) x M (\text{Fn } y T (\text{THE } X. \text{substitutes } A x M X))$ 
using  $A'$  unfolding subst-def by metis

```

```

fix  $X$ 
assume substitutes  $(\text{Fn } y T A) x M X$ 
thus  $X = \text{Fn } y T (\text{THE } X. \text{substitutes } A x M X)$  using substitutes-function *
by metis
qed

```

```

lemma subst-simp-pair:
shows  $(\text{Pair } A B)[x ::= M] = \text{Pair } (A[x ::= M]) (B[x ::= M])$ 
unfolding subst-def proof
obtain  $A' B'$  where  $A': A' = (A[x ::= M])$  and  $B': B' = (B[x ::= M])$  by auto
hence substitutes  $A x M A'$  substitutes  $B x M B'$ 

```

unfolding *subst-def* **using** *substitutes-function theI* **by** *metis+*
hence *substitutes (Pair A B) x M (Pair A' B')* **using** *substitutes.pair* **by** *metis*
thus $*$: *substitutes (Pair A B) x M (Pair (THE X. substitutes A x M X) (THE X. substitutes B x M X))*
using *A' B' unfolding subst-def by metis*

fix *X*
assume *substitutes (Pair A B) x M X*
thus $X = \text{Pair } (THE\ X.\ \text{substitutes } A\ x\ M\ X)\ (THE\ X.\ \text{substitutes } B\ x\ M\ X)$
using *substitutes-function * by metis*
qed

lemma *subst-simp-fst*:
shows $(Fst\ P)[x ::= M] = Fst\ (P[x ::= M])$
unfolding *subst-def* **proof**
obtain P' **where** $P': P' = (P[x ::= M])$ **by** *auto*
hence *substitutes P x M P'* **unfolding** *subst-def* **using** *substitutes-function theI*
by *metis*
hence *substitutes (Fst P) x M (Fst P')* **using** *substitutes.fst* **by** *metis*
thus $*$: *substitutes (Fst P) x M (Fst (THE X. substitutes P x M X))*
using P' **unfolding** *subst-def* **by** *metis*

fix *X*
assume *substitutes (Fst P) x M X*
thus $X = Fst\ (THE\ X.\ \text{substitutes } P\ x\ M\ X)$ **using** *substitutes-function * by metis*
qed

lemma *subst-simp-snd*:
shows $(Snd\ P)[x ::= M] = Snd\ (P[x ::= M])$
unfolding *subst-def* **proof**
obtain P' **where** $P': P' = (P[x ::= M])$ **by** *auto*
hence *substitutes P x M P'* **unfolding** *subst-def* **using** *substitutes-function theI*
by *metis*
hence *substitutes (Snd P) x M (Snd P')* **using** *substitutes.snd* **by** *metis*
thus $*$: *substitutes (Snd P) x M (Snd (THE X. substitutes P x M X))*
using P' **unfolding** *subst-def* **by** *metis*

fix *X*
assume *substitutes (Snd P) x M X*
thus $X = Snd\ (THE\ X.\ \text{substitutes } P\ x\ M\ X)$ **using** *substitutes-function * by metis*
qed

lemma *subst-prm*:
shows $(\pi \cdot (M[z ::= N])) = ((\pi \cdot M)[\pi\ \$\ z ::= \pi \cdot N])$
unfolding *subst-def* **using** *substitutes-prm substitutes-function the1-equality by (metis (full-types))*

```

lemma subst-fvs:
  shows  $fvs (M[z ::= N]) \subseteq (fvs M - \{z\}) \cup fvs N$ 
unfolding subst-def using substitutes-fvs substitutes-function theI2 by metis

lemma subst-free:
  assumes  $y \notin fvs M$ 
  shows  $M[y ::= N] = M$ 
using assms proof(induction M rule: trm-strong-induct[where S={y} \cup fvs N])
  show finite ( $\{y\} \cup fvs N$ ) using fvs-finite by auto

  case 1
    thus ?case using subst-simp-unit by metis
  next
  case (2 x)
    thus ?case using subst-simp-var2 by (simp add: fvs-simp)
  next
  case (3 A B)
    thus ?case using subst-simp-app by (simp add: fvs-simp)
  next
  case (4 x T A)
    hence  $y \neq x \wedge x \notin fvs N$  by auto

    have  $y \notin fvs A - \{x\}$  using  $\langle y \neq x \rangle \langle y \notin fvs (Fn x T A) \rangle$  fvs-simp(4) by
    metis
    hence  $y \notin fvs A$  using  $\langle y \neq x \rangle$  by auto
    hence  $A[y ::= N] = A$  using 4.IH by blast
    thus ?case using  $\langle y \neq x \rangle \langle y \notin fvs A \rangle \langle x \notin fvs N \rangle$  subst-simp-fn by metis
  next
  case (5 A B)
    thus ?case using subst-simp-pair by (simp add: fvs-simp)
  next
  case (6 P)
    thus ?case using subst-simp-fst by (simp add: fvs-simp)
  next
  case (7 P)
    thus ?case using subst-simp-snd by (simp add: fvs-simp)
  next
qed

lemma subst-swp:
  assumes  $y \notin fvs A$ 
  shows  $([y \leftrightarrow z] \cdot A)[y ::= M] = (A[z ::= M])$ 
using assms proof(induction A rule: trm-strong-induct[where S={y, z} \cup fvs M])
  show finite ( $\{y, z\} \cup fvs M$ ) using fvs-finite by auto
  next

  case 1
    thus ?case using trm-prm-simp(1) subst-simp-unit by metis

```

```

next
case (2 x)
  hence  $y \neq x$  using fvs-simp(2) by force
  consider  $x = z \mid x \neq z$  by auto
  thus ?case proof(cases)
    case 1
      thus ?thesis using subst-simp-var1 trm-prm-simp(2) prm-unit-action
prm-unit-commutes by metis
    next
    case 2
      thus ?thesis using subst-simp-var2 trm-prm-simp(2) prm-unit-inaction  $\langle y \neq x \rangle$  by metis
    next
    qed
  next
case (3 A B)
  from  $\langle y \notin \text{fvs } (App\ A\ B) \rangle$  have  $y \notin \text{fvs } A\ y \notin \text{fvs } B$  by (auto simp add:
fvs-simp(3))
  thus ?case using 3.IH subst-simp-app trm-prm-simp(3) by metis
  next
case (4 x T A)
  hence  $x \neq y\ x \neq z\ x \notin \text{fvs } M$  by auto
  hence  $y \notin \text{fvs } A$  using  $\langle y \notin \text{fvs } (Fn\ x\ T\ A) \rangle$  fvs-simp(4) by force
  hence *:  $([y \leftrightarrow z] \cdot A)[y ::= M] = (A[z ::= M])$  using 4.IH by metis

  have  $([y \leftrightarrow z] \cdot Fn\ x\ T\ A)[y ::= M] = ((Fn\ ([y \leftrightarrow z]\ \$\ x)\ T\ ([y \leftrightarrow z] \cdot A))[y ::= M])$ 
  using trm-prm-simp(4) by metis
  also have ... =  $((Fn\ x\ T\ ([y \leftrightarrow z] \cdot A))[y ::= M])$ 
  using prm-unit-inaction  $\langle x \neq y \rangle\ \langle x \neq z \rangle$  by metis
  also have ... =  $Fn\ x\ T\ ([y \leftrightarrow z] \cdot A)[y ::= M]$ 
  using subst-simp-fn  $\langle x \neq y \rangle\ \langle x \notin \text{fvs } M \rangle$  by metis
  also have ... =  $Fn\ x\ T\ (A[z ::= M])$  using * by metis
  also have ... =  $((Fn\ x\ T\ A)[z ::= M])$ 
  using subst-simp-fn  $\langle x \neq z \rangle\ \langle x \notin \text{fvs } M \rangle$  by metis
  finally show ?case.
  next
case (5 A B)
  from  $\langle y \notin \text{fvs } (Pair\ A\ B) \rangle$  have  $y \notin \text{fvs } A\ y \notin \text{fvs } B$  by (auto simp add:
fvs-simp(5))
  hence  $([y \leftrightarrow z] \cdot A)[y ::= M] = (A[z ::= M])\ ([y \leftrightarrow z] \cdot B)[y ::= M] = (B[z ::= M])$ 
  using 5.IH by metis+
  thus ?case using trm-prm-simp(5) subst-simp-pair by metis
  next
case (6 P)
  from  $\langle y \notin \text{fvs } (Fst\ P) \rangle$  have  $y \notin \text{fvs } P$  by (simp add: fvs-simp(6))
  hence  $([y \leftrightarrow z] \cdot P)[y ::= M] = (P[z ::= M])$  using 6.IH by metis
  thus ?case using trm-prm-simp(6) subst-simp-fst by metis

```

```

next
case (7 P)
  from ⟨y ∉ fvs (Snd P)⟩ have y ∉ fvs P by (simp add: fvs-simp(7))
  hence ([y ↔ z] · P)[y ::= M] = (P[z ::= M]) using 7.IH by metis
  thus ?case using trm-prm-simp(7) subst-simp-snd by metis
next
qed

lemma barendregt:
  assumes y ≠ z y ∉ fvs L
  shows M[y ::= N][z ::= L] = (M[z ::= L][y ::= N[z ::= L]])
using assms proof(induction M rule: trm-strong-induct[where S={y, z} ∪ fvs N
∪ fvs L])
  show finite ({y, z} ∪ fvs N ∪ fvs L) using fvs-finite by auto
  next

  case 1
  thus ?case using subst-simp-unit by metis
  next
  case (2 x)
  consider x = y | x = z | x ≠ y ∧ x ≠ z by auto
  thus ?case proof(cases)
    case 1
    hence x = y x ≠ z using assms(1) by auto
    thus ?thesis using subst-simp-var1 subst-simp-var2 by metis
    next
    case 2
    hence x ≠ y x = z using assms(1) by auto
    thus ?thesis using subst-free ⟨y ∉ fvs L⟩ subst-simp-var1 subst-simp-var2
by metis
  next
  case 3
  then show ?thesis using subst-simp-var2 by metis
  next
  qed
  next
  case (3 A B)
  thus ?case using subst-simp-app by metis
  next
  case (4 x T A)
  hence *: A[y ::= N][z ::= L] = (A[z ::= L][y ::= N[z ::= L]]) by blast
  from ⟨x ∉ {y, z} ∪ fvs N ∪ fvs L⟩ have x ≠ y x ≠ z x ∉ fvs N x ∉ fvs L by
auto
  hence x ∉ fvs (N[z ::= L]) using subst-fvs by auto

  have (Fn x T A)[y ::= N][z ::= L] = Fn x T (A[y ::= N][z ::= L])
  using subst-simp-fn ⟨x ≠ y⟩ ⟨x ≠ z⟩ ⟨x ∉ fvs N⟩ ⟨x ∉ fvs L⟩ by metis
  also have ... = Fn x T (A[z ::= L][y ::= N[z ::= L]]) using * by metis
  also have ... = ((Fn x T A)[z ::= L][y ::= N[z ::= L]])

```

using *subst-simp-fn* $\langle x \neq y \rangle \langle x \neq z \rangle \langle x \notin \text{fvs} (N[z ::= L]) \rangle \langle x \notin \text{fvs} L \rangle$ **by**
metis
finally show *?case*.
next
case (5 *A B*)
thus *?case* **using** *subst-simp-pair* **by** *metis*
next
case (6 *P*)
thus *?case* **using** *subst-simp-fst* **by** *metis*
next
case (7 *P*)
thus *?case* **using** *subst-simp-snd* **by** *metis*
next
qed

lemma *typing-subst*:
assumes $\Gamma(z \mapsto \tau) \vdash M : \sigma \quad \Gamma \vdash N : \tau$
shows $\Gamma \vdash M[z ::= N] : \sigma$
using *assms* **proof**(*induction M arbitrary: $\Gamma \sigma$ rule: trm-strong-depth-induct*[**where**
 $S = \{z\} \cup \text{fvs} N$])
show *finite* ($\{z\} \cup \text{fvs} N$) **using** *fvs-finite* **by** *auto*
next

case 1
thus *?case* **using** *subst-simp-unit* *typing.tunit* *typing-unitE* **by** *metis*
next
case (2 *x*)
hence $*$: $(\Gamma(z \mapsto \tau)) \ x = \text{Some } \sigma$ **using** *typing-varE* **by** *metis*

consider $x = z \mid x \neq z$ **by** *auto*
thus *?case* **proof**(*cases*)
case 1
hence $(\Gamma(x \mapsto \tau)) \ x = \text{Some } \sigma$ **using** $*$ **by** *metis*
hence $\tau = \sigma$ **by** *auto*
thus *?thesis* **using** $\langle \Gamma \vdash N : \tau \rangle$ *subst-simp-var1* $\langle x = z \rangle$ **by** *metis*
next
case 2
hence $\Gamma \ x = \text{Some } \sigma$ **using** $*$ **by** *auto*
hence $\Gamma \vdash \text{Var } x : \sigma$ **using** *typing.tvar* **by** *metis*
thus *?thesis* **using** $\langle x \neq z \rangle$ *subst-simp-var2* **by** *metis*
next

qed
next
case (3 *A B*)
have $*$: $\text{depth } A < \text{depth } (\text{App } A \ B) \wedge \text{depth } B < \text{depth } (\text{App } A \ B)$
using *depth-app* **by** *auto*

from $\langle \Gamma(z \mapsto \tau) \vdash \text{App } A \ B : \sigma \rangle$ **obtain** σ' **where**
 $\Gamma(z \mapsto \tau) \vdash A : (\text{TArr } \sigma' \ \sigma)$

$\Gamma(z \mapsto \tau) \vdash B : \sigma'$
using *typing-appE* **by** *metis*
hence
 $\Gamma \vdash (A[z ::= N]) : (TArr \sigma' \sigma)$
 $\Gamma \vdash (B[z ::= N]) : \sigma'$
using β * **by** *metis+*
hence $\Gamma \vdash App (A[z ::= N]) (B[z ::= N]) : \sigma$ **using** *typing.tapp* **by** *metis*
thus *?case* **using** *subst-simp-app* **by** *metis*
next
case (4 $x T A$)
hence $x \neq z \ x \notin fvs N$ **by** *auto*
hence *: $\Gamma(x \mapsto T) \vdash N : \tau$ **using** *typing-weaken* 4 **by** *metis*
have **: $depth A < depth (Fn x T A)$ **using** *depth-fn*.

from $\langle \Gamma(z \mapsto \tau) \vdash Fn x T A : \sigma \rangle$ **obtain** σ' **where**
 $\sigma = TArr T \sigma'$
 $\Gamma(z \mapsto \tau, x \mapsto T) \vdash A : \sigma'$
using *typing-fnE* **by** *metis*
hence $\Gamma(x \mapsto T, z \mapsto \tau) \vdash A : \sigma'$ **using** $\langle x \neq z \rangle$ *fun-upd-twist* **by** *metis*
hence $\Gamma(x \mapsto T) \vdash A[z ::= N] : \sigma'$ **using** 4 * ** **by** *metis*
hence $\Gamma \vdash Fn x T (A[z ::= N]) : \sigma$ **using** *typing.tfn* $\langle \sigma = TArr T \sigma' \rangle$ **by** *metis*
thus *?case* **using** $\langle x \neq z \rangle \langle x \notin fvs N \rangle$ *subst-simp-fn* **by** *metis*
next
case (5 $A B$)
from *this* **obtain** $T S$ **where** $\sigma = TPair T S$ $\Gamma(z \mapsto \tau) \vdash A : T$ $\Gamma(z \mapsto \tau) \vdash B : S$
using *typing-pairE* **by** *metis*
moreover **have** $depth A < depth (Pair A B)$ **and** $depth B < depth (Pair A B)$
using *depth-pair* **by** *auto*
ultimately **have** $\Gamma \vdash A[z ::= N] : T$ $\Gamma \vdash B[z ::= N] : S$ **using** 5 **by** *metis+*
hence $\Gamma \vdash Pair (A[z ::= N]) (B[z ::= N]) : \sigma$ **using** $\langle \sigma = TPair T S \rangle$ *typing.tpair* **by** *metis*
thus *?case* **using** *subst-simp-pair* **by** *metis*
next
case (6 P)
from *this* **obtain** σ' **where** $\Gamma(z \mapsto \tau) \vdash P : (TPair \sigma \sigma')$ **using** *typing-fstE* **by** *metis*
moreover **have** $depth P < depth (Fst P)$ **using** *depth-fst* **by** *metis*
ultimately **have** $\Gamma \vdash P[z ::= N] : (TPair \sigma \sigma')$ **using** 6 **by** *metis*
hence $\Gamma \vdash Fst (P[z ::= N]) : \sigma$ **using** *typing.tfst* **by** *metis*
thus *?case* **using** *subst-simp-fst* **by** *metis*
next
case (7 P)
from *this* **obtain** σ' **where** $\Gamma(z \mapsto \tau) \vdash P : (TPair \sigma' \sigma)$ **using** *typing-sndE* **by** *metis*
moreover **have** $depth P < depth (Snd P)$ **using** *depth-snd* **by** *metis*
ultimately **have** $\Gamma \vdash P[z ::= N] : (TPair \sigma' \sigma)$ **using** 7 **by** *metis*
hence $\Gamma \vdash Snd (P[z ::= N]) : \sigma$ **using** *typing.tsnd* **by** *metis*

```

  thus ?case using subst-simp-snd by metis
next
qed

```

inductive *beta-reduction* :: 'a trm \Rightarrow 'a trm \Rightarrow bool ($- \rightarrow\beta -$) **where**

```

  beta: (App (Fn x T A) M)  $\rightarrow\beta$  (A[x ::= M])
| app1: A  $\rightarrow\beta$  A'  $\Longrightarrow$  (App A B)  $\rightarrow\beta$  (App A' B)
| app2: B  $\rightarrow\beta$  B'  $\Longrightarrow$  (App A B)  $\rightarrow\beta$  (App A B')
| fn:   A  $\rightarrow\beta$  A'  $\Longrightarrow$  (Fn x T A)  $\rightarrow\beta$  (Fn x T A')
| pair1: A  $\rightarrow\beta$  A'  $\Longrightarrow$  (Pair A B)  $\rightarrow\beta$  (Pair A' B)
| pair2: B  $\rightarrow\beta$  B'  $\Longrightarrow$  (Pair A B)  $\rightarrow\beta$  (Pair A B')
| fst1: P  $\rightarrow\beta$  P'  $\Longrightarrow$  (Fst P)  $\rightarrow\beta$  (Fst P')
| fst2: (Fst (Pair A B))  $\rightarrow\beta$  A
| snd1: P  $\rightarrow\beta$  P'  $\Longrightarrow$  (Snd P)  $\rightarrow\beta$  (Snd P')
| snd2: (Snd (Pair A B))  $\rightarrow\beta$  B

```

lemma *beta-reduction-fvs*:

```

  assumes M  $\rightarrow\beta$  M'
  shows fvs M'  $\subseteq$  fvs M
using assms proof(induction)
  case (beta x T A M)
    thus ?case using fvs-simp(3) fvs-simp(4) subst-fvs by metis
  next
  case (app1 A A' B)
    hence fvs A'  $\cup$  fvs B  $\subseteq$  fvs A  $\cup$  fvs B by auto
    thus ?case using fvs-simp(3) by metis
  next
  case (app2 B B' A)
    hence fvs A  $\cup$  fvs B'  $\subseteq$  fvs A  $\cup$  fvs B by auto
    thus ?case using fvs-simp(3) by metis
  next
  case (fn A A' x T)
    hence fvs A' - {x}  $\subseteq$  fvs A - {x} by auto
    thus ?case using fvs-simp(4) by metis
  next
  case (pair1 A A' B)
    hence fvs A'  $\cup$  fvs B  $\subseteq$  fvs A  $\cup$  fvs B by auto
    thus ?case using fvs-simp(5) by metis
  next
  case (pair2 B B' A)
    hence fvs A  $\cup$  fvs B'  $\subseteq$  fvs A  $\cup$  fvs B by auto
    thus ?case using fvs-simp(5) by metis
  next
  case (fst1 P P')
    thus ?case using fvs-simp(6) by metis
  next
  case (fst2 A B)
    thus ?case using fvs-simp(5, 6) by force

```

```

next
case (snd1 P P')
  thus ?case using fvs-simp( $\gamma$ ) by metis
next
case (snd2 A B)
  thus ?case using fvs-simp(5,  $\gamma$ ) by force
next
qed

```

lemma *beta-reduction-prm*:
assumes $M \rightarrow\beta M'$
shows $(\pi \cdot M) \rightarrow\beta (\pi \cdot M')$
using *assms* **by**(*induction, auto simp add: beta-reduction.intros trm-prm-simp subst-prm*)

lemma *beta-reduction-left-unitE*:
assumes $Unit \rightarrow\beta M'$
shows *False*
using *assms* **by**(*cases, auto simp add: unit-not-app unit-not-fn unit-not-pair unit-not-fst unit-not-snd*)

lemma *beta-reduction-left-varE*:
assumes $(Var\ x) \rightarrow\beta M'$
shows *False*
using *assms* **by**(*cases, auto simp add: var-not-app var-not-fn var-not-pair var-not-fst var-not-snd*)

lemma *beta-reduction-left-appE*:
assumes $(App\ A\ B) \rightarrow\beta M'$
shows
 $(\exists x\ T\ X. A = (Fn\ x\ T\ X) \wedge M' = (X[x ::= B])) \vee$
 $(\exists A'. (A \rightarrow\beta A') \wedge M' = App\ A'\ B) \vee$
 $(\exists B'. (B \rightarrow\beta B') \wedge M' = App\ A\ B')$

using *assms* **by**(
cases,
metis trm-simp(2, 3),
metis trm-simp(2, 3),
metis trm-simp(2, 3),
auto simp add: app-not-fn app-not-pair app-not-fst app-not-snd
)

lemma *beta-reduction-left-fnE*:
assumes $(Fn\ x\ T\ A) \rightarrow\beta M'$
shows $\exists A'. (A \rightarrow\beta A') \wedge M' = (Fn\ x\ T\ A')$
using *assms* **proof**(*cases*)
case $(fn\ B\ B'\ y\ S)$
consider $x = y \wedge T = S \wedge A = B \mid x \neq y \wedge T = S \wedge x \notin fvs\ B \wedge A = [x$
 $\leftrightarrow y] \cdot B$
using *trm-simp(4)* $\langle Fn\ x\ T\ A = Fn\ y\ S\ B \rangle$ **by** *metis*

```

thus ?thesis proof(cases)
  case 1
    thus ?thesis using fn by auto
  next
  case 2
    thus ?thesis using fn beta-reduction-fvs beta-reduction-prm fn-eq by fastforce
  next
  qed
next
qed (
  metis app-not-fn,
  metis app-not-fn,
  metis app-not-fn,
  auto simp add: fn-not-pair fn-not-fst fn-not-snd
)

```

```

lemma beta-reduction-left-pairE:
  assumes (Pair A B)  $\rightarrow\beta$  M'
  shows  $(\exists A'. (A \rightarrow\beta A') \wedge M' = (\text{Pair } A' B)) \vee (\exists B'. (B \rightarrow\beta B') \wedge M' = (\text{Pair } A B'))$ 
using assms
  apply cases
  prefer 5
  apply (metis trm-simp(5, 6))
  prefer 5
  apply (metis trm-simp(5, 6))
  apply (metis app-not-pair, metis app-not-pair, metis app-not-pair, metis fn-not-pair,
  metis pair-not-fst, metis pair-not-fst, metis pair-not-snd, metis pair-not-snd)
done

```

```

lemma beta-reduction-left-fstE:
  assumes (Fst P)  $\rightarrow\beta$  M'
  shows  $(\exists P'. (P \rightarrow\beta P') \wedge M' = (\text{Fst } P')) \vee (\exists A B. P = (\text{Pair } A B) \wedge M' = A)$ 
using assms proof(cases)
  case (fst1 P P')
    thus ?thesis using trm-simp(7) by blast
  next
  case (fst2 B)
    thus ?thesis using trm-simp(7) by blast
  next
qed (
  metis app-not-fst,
  metis app-not-fst,
  metis app-not-fst,
  metis fn-not-fst,
  metis pair-not-fst,
  metis pair-not-fst,
  metis fst-not-snd,
)

```

metis fst-not-snd
)

lemma *beta-reduction-left-sndE*:

assumes $(\text{Snd } P) \rightarrow\beta M'$

shows $(\exists P'. (P \rightarrow\beta P') \wedge M' = (\text{Snd } P')) \vee (\exists A B. P = \text{Pair } A B \wedge M' = B)$

using *assms* **proof**(*cases*)

case (*snd1* $P P'$)

thus *?thesis* **using** *trm-simp*(δ) **by** *blast*

next

case (*snd2* A)

thus *?thesis* **using** *trm-simp*(δ) **by** *blast*

next

qed (

metis app-not-snd,

metis app-not-snd,

metis app-not-snd,

metis fn-not-snd,

metis pair-not-snd,

metis pair-not-snd,

metis fst-not-snd,

metis fst-not-snd

)

lemma *preservation'*:

assumes $\Gamma \vdash M : \tau$ **and** $M \rightarrow\beta M'$

shows $\Gamma \vdash M' : \tau$

using *assms* **proof**(*induction arbitrary: M' rule: typing.induct*)

case (*tunit* Γ)

thus *?case* **using** *beta-reduction-left-unitE* **by** *metis*

next

case (*tvar* $\Gamma x \tau$)

thus *?case* **using** *beta-reduction-left-varE* **by** *metis*

next

case (*tapp* $\Gamma A \tau \sigma B M'$)

from $\langle (\text{App } A B) \rightarrow\beta M' \rangle$ **consider**

$(\exists x T X. A = (\text{Fn } x T X) \wedge M' = (X[x ::= B])) \mid$

$(\exists A'. (A \rightarrow\beta A') \wedge M' = \text{App } A' B) \mid$

$(\exists B'. (B \rightarrow\beta B') \wedge M' = \text{App } A B')$ **using** *beta-reduction-left-appE* **by** *metis*

thus *?case* **proof**(*cases*)

case *1*

from *this* **obtain** $x T X$ **where** $A = \text{Fn } x T X$ **and** $*$: $M' = (X[x ::= B])$

by *auto*

have $\Gamma(x \mapsto \tau) \vdash X : \sigma$ **using** *typing-fnE* $\langle \Gamma \vdash A : (\text{TArr } \tau \sigma) \rangle \langle A = \text{Fn } x T X \rangle$ *type.inject*

by *blast*

hence $\Gamma \vdash (X[x ::= B]) : \sigma$ **using** *typing-subst* $\langle \Gamma \vdash B : \tau \rangle$ **by** *metis*

thus *?thesis* **using** * **by** *auto*
next
case 2
from *this* **obtain** A' **where** $A \rightarrow\beta A'$ **and** $*$: $M' = (App\ A'\ B)$ **by** *auto*
hence $\Gamma \vdash A' : (TArr\ \tau\ \sigma)$ **using** *tapp.IH(1)* **by** *metis*
hence $\Gamma \vdash (App\ A'\ B) : \sigma$ **using** $\langle \Gamma \vdash B : \tau \rangle$ *typing.tapp* **by** *metis*
thus *?thesis* **using** * **by** *auto*
next
case 3
from *this* **obtain** B' **where** $B \rightarrow\beta B'$ **and** $*$: $M' = (App\ A\ B')$ **by** *auto*
hence $\Gamma \vdash B' : \tau$ **using** *tapp.IH(2)* **by** *metis*
hence $\Gamma \vdash (App\ A\ B') : \sigma$ **using** $\langle \Gamma \vdash A : (TArr\ \tau\ \sigma) \rangle$ *typing.tapp* **by** *metis*
thus *?thesis* **using** * **by** *auto*
next
qed
next
case (*tfn* $\Gamma\ x\ T\ A\ \sigma$)
from *this* **obtain** A' **where** $A \rightarrow\beta A'$ **and** $*$: $M' = (Fn\ x\ T\ A')$
using *beta-reduction-left-fnE* **by** *metis*
hence $\Gamma(x \mapsto T) \vdash A' : \sigma$ **using** *tfn.IH* **by** *metis*
hence $\Gamma \vdash (Fn\ x\ T\ A') : (TArr\ T\ \sigma)$ **using** *typing.tfn* **by** *metis*
thus *?case* **using** * **by** *auto*
next
case (*tpair* $\Gamma\ A\ \tau\ B\ \sigma$)
from *this* **consider**
 $\exists A'. (A \rightarrow\beta A') \wedge M' = (Pair\ A'\ B)$
 $|\ \exists B'. (B \rightarrow\beta B') \wedge M' = (Pair\ A\ B')$
using *beta-reduction-left-pairE* **by** *metis*
thus *?case* **proof**(*cases*)
case 1
from *this* **obtain** A' **where** $A \rightarrow\beta A'$ **and** $M' = Pair\ A'\ B$ **by** *auto*
thus *?thesis* **using** *tpair* *typing.tpair* **by** *metis*
next
case 2
from *this* **obtain** B' **where** $B \rightarrow\beta B'$ **and** $M' = Pair\ A\ B'$ **by** *auto*
thus *?thesis* **using** *tpair* *typing.tpair* **by** *metis*
next
qed
next
case (*tfst* $\Gamma\ P\ \tau\ \sigma$)
from *this* **consider**
 $\exists P'. (P \rightarrow\beta P') \wedge M' = Fst\ P'$
 $|\ \exists A\ B. P = Pair\ A\ B \wedge M' = A$ **using** *beta-reduction-left-fstE* **by** *metis*
thus *?case* **proof**(*cases*)
case 1
from *this* **obtain** P' **where** $P \rightarrow\beta P'$ **and** $M' = Fst\ P'$ **by** *auto*
thus *?thesis* **using** *tfst* *typing.tfst* **by** *metis*
next
case 2

from this obtain $A B$ **where** $P = \text{Pair } A B$ **and** $M' = A$ **by auto**
thus ?thesis using $\langle \Gamma \vdash P : (TPair \tau \sigma) \rangle$ *typing-pairE* **by blast**
next
qed
next
case ($tsnd \Gamma P \tau \sigma$)
from this consider
 $\exists P'. (P \rightarrow \beta P') \wedge M' = Snd P'$
 $|\exists A B. P = \text{Pair } A B \wedge M' = B$ **using** *beta-reduction-left-sndE* **by metis**
thus ?case proof(*cases*)
case 1
from this obtain P' **where** $P \rightarrow \beta P'$ **and** $M' = Snd P'$ **by auto**
thus ?thesis using *tsnd typing.tsnd* **by metis**
next
case 2
from this obtain $A B$ **where** $P = \text{Pair } A B$ **and** $M' = B$ **by auto**
thus ?thesis using $\langle \Gamma \vdash P : (TPair \tau \sigma) \rangle$ *typing-pairE* **by blast**
next
qed
next
qed

inductive $NF :: 'a \text{ trm} \Rightarrow \text{bool}$ **where**
unit: NF Unit
 $| \text{var: } NF (\text{Var } x)$
 $| \text{app: } \llbracket A \neq \text{Fn } x T A'; NF A; NF B \rrbracket \Longrightarrow NF (\text{App } A B)$
 $| \text{fn: } NF A \Longrightarrow NF (\text{Fn } x T A)$
 $| \text{pair: } \llbracket NF A; NF B \rrbracket \Longrightarrow NF (\text{Pair } A B)$
 $| \text{fst: } \llbracket P \neq \text{Pair } A B; NF P \rrbracket \Longrightarrow NF (\text{Fst } P)$
 $| \text{snd: } \llbracket P \neq \text{Pair } A B; NF P \rrbracket \Longrightarrow NF (\text{Snd } P)$

theorem *progress*:
assumes $\Gamma \vdash M : \tau$
shows $NF M \vee (\exists M'. (M \rightarrow \beta M'))$
using *assms proof*(*induction M arbitrary: \Gamma \tau rule: trm-induct*)
case 1
thus ?case using *NF.unit* **by metis**
next
case ($2 x$)
thus ?case using *NF.var* **by metis**
next
case ($3 A B$)
from $\langle \Gamma \vdash \text{App } A B : \tau \rangle$ **obtain** σ
where $\Gamma \vdash A : (TArr \sigma \tau)$ **and** $\Gamma \vdash B : \sigma$
using *typing-appE* **by metis**
hence $A: NF A \vee (\exists A'. (A \rightarrow \beta A'))$ **and** $B: NF B \vee (\exists B'. (B \rightarrow \beta B'))$
using $3.IH$ **by auto**

consider $NF B | \exists B'. (B \rightarrow \beta B')$ **using** B **by auto**

```

thus ?case proof(cases)
  case 1
    consider  $NF\ A \mid \exists A'. (A \rightarrow\beta\ A')$  using  $A$  by auto
    thus ?thesis proof(cases)
      case 1
        consider  $\exists x\ T\ A'. A = Fn\ x\ T\ A' \mid \nexists x\ T\ A'. A = Fn\ x\ T\ A'$  by auto
        thus ?thesis proof(cases)
          case 1
            from this obtain  $x\ T\ A'$  where  $A = Fn\ x\ T\ A'$  by auto
            hence  $(App\ A\ B) \rightarrow\beta\ (A'[x ::= B])$  using beta-reduction.beta by
metis
              thus ?thesis by blast
            next
              case 2
                thus ?thesis using  $\langle NF\ A \rangle\ \langle NF\ B \rangle\ NF.app$  by metis
              next
                qed
              next
                case 2
                  thus ?thesis using beta-reduction.app1 by metis
                next
                  qed
              next
                case 2
                  thus ?thesis using beta-reduction.app2 by metis
                next
                  qed
              next
                case 2
                  from  $\langle \Gamma \vdash Fn\ x\ T\ A : \tau \rangle$  obtain  $\sigma$ 
                  where  $\tau = TArr\ T\ \sigma$  and  $\Gamma(x \mapsto T) \vdash A : \sigma$ 
                  using typing-fnE by metis
                  from  $\langle \Gamma(x \mapsto T) \vdash A : \sigma \rangle$  consider  $NF\ A \mid \exists A'. (A \rightarrow\beta\ A')$ 
                  using 4.IH by metis

thus ?case proof(cases)
  case 1
    thus ?thesis using NF.fn by metis
  next
    case 2
      from this obtain  $A'$  where  $A \rightarrow\beta\ A'$  by auto
      obtain  $M'$  where  $M' = Fn\ x\ T\ A'$  by auto
      hence  $(Fn\ x\ T\ A) \rightarrow\beta\ M'$  using  $\langle A \rightarrow\beta\ A' \rangle$  beta-reduction.fn by metis
      thus ?thesis by auto
    next
      qed
  next
    case (5  $A\ B$ )
      thus ?case using typing-pairE beta-reduction.pair1 beta-reduction.pair2 NF.pair

```

```

by meson
next
case (6 P)
  from this consider NF P |  $\exists P'. (P \rightarrow\beta P')$  using typing-fstE by metis
  thus ?case proof(cases)
  case 1
    consider  $\exists A B. P = \text{Pair } A B$  |  $\nexists A B. P = \text{Pair } A B$  by auto
    thus ?thesis proof(cases)
    case 1
      from this obtain A B where P = Pair A B by auto
      hence (Fst P)  $\rightarrow\beta A$  using beta-reduction.fst2 by metis
      thus ?thesis by auto
    next
    case 2
      thus ?thesis using  $\langle NF P \rangle NF.fst$  by metis
    next
  qed
next
case 2
  thus ?thesis using beta-reduction.fst1 by metis
next
qed
next
case (7 P)
  from this consider NF P |  $\exists P'. (P \rightarrow\beta P')$  using typing-sndE by metis
  thus ?case proof(cases)
  case 1
    consider  $\exists A B. P = \text{Pair } A B$  |  $\nexists A B. P = \text{Pair } A B$  by auto
    thus ?thesis proof(cases)
    case 1
      from this obtain A B where P = Pair A B by auto
      hence (Snd P)  $\rightarrow\beta B$  using beta-reduction.snd2 by metis
      thus ?thesis by auto
    next
    case 2
      thus ?thesis using  $\langle NF P \rangle NF.snd$  by metis
    next
  qed
next
case 2
  thus ?thesis using beta-reduction.snd1 by metis
next
qed
next
qed

```

inductive beta-reduces :: 'a trm \Rightarrow 'a trm \Rightarrow bool ($- \rightarrow\beta^* -$) **where**
reflexive: $M \rightarrow\beta^* M$
| transitive: $\llbracket M \rightarrow\beta^* M'; M' \rightarrow\beta M'' \rrbracket \Longrightarrow M \rightarrow\beta^* M''$

```

lemma beta-reduces-composition:
  assumes  $A' \rightarrow_{\beta^*} A''$  and  $A \rightarrow_{\beta^*} A'$ 
  shows  $A \rightarrow_{\beta^*} A''$ 
using assms proof(induction)
  case (reflexive  $B$ )
    thus ?case.
  next
  case (transitive  $B B' B''$ )
    thus ?case using beta-reduces.transitive by metis
  next
qed

lemma beta-reduces-fvs:
  assumes  $A \rightarrow_{\beta^*} A'$ 
  shows  $fvs A' \subseteq fvs A$ 
using assms proof(induction)
  case (reflexive  $M$ )
    thus ?case by auto
  next
  case (transitive  $M M' M''$ )
    hence  $fvs M'' \subseteq fvs M'$  using beta-reduction-fvs by metis
    thus ?case using  $\langle fvs M' \subseteq fvs M \rangle$  by auto
  next
qed

lemma beta-reduces-app-left:
  assumes  $A \rightarrow_{\beta^*} A'$ 
  shows  $(App A B) \rightarrow_{\beta^*} (App A' B)$ 
using assms proof(induction)
  case (reflexive  $A$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (transitive  $A A' A''$ )
    thus ?case using beta-reduces.transitive beta-reduction.app1 by metis
  next
qed

lemma beta-reduces-app-right:
  assumes  $B \rightarrow_{\beta^*} B'$ 
  shows  $(App A B) \rightarrow_{\beta^*} (App A B')$ 
using assms proof(induction)
  case (reflexive  $B$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (transitive  $B B' B''$ )
    thus ?case using beta-reduces.transitive beta-reduction.app2 by metis
  next
qed

```

```

lemma beta-reduces-fn:
  assumes  $A \rightarrow\beta^* A'$ 
  shows  $(\text{Fn } x \ T \ A) \rightarrow\beta^* (\text{Fn } x \ T \ A')$ 
using assms proof(induction)
  case (reflexive  $A$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (transitive  $A \ A' \ A''$ )
    thus ?case using beta-reduces.transitive beta-reduction.fn by metis
  next
qed

lemma beta-reduces-pair-left:
  assumes  $A \rightarrow\beta^* A'$ 
  shows  $(\text{Pair } A \ B) \rightarrow\beta^* (\text{Pair } A' \ B)$ 
using assms proof(induction)
  case (reflexive  $M$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (transitive  $M \ M' \ M''$ )
    thus ?case using beta-reduces.transitive beta-reduction.pair1 by metis
  next
qed

lemma beta-reduces-pair-right:
  assumes  $B \rightarrow\beta^* B'$ 
  shows  $(\text{Pair } A \ B) \rightarrow\beta^* (\text{Pair } A \ B')$ 
using assms proof(induction)
  case (reflexive  $M$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (transitive  $M \ M' \ M''$ )
    thus ?case using beta-reduces.transitive beta-reduction.pair2 by metis
  next
qed

lemma beta-reduces-fst:
  assumes  $P \rightarrow\beta^* P'$ 
  shows  $(\text{Fst } P) \rightarrow\beta^* (\text{Fst } P')$ 
using assms proof(induction)
  case (reflexive  $M$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (transitive  $M \ M' \ M''$ )
    thus ?case using beta-reduces.transitive beta-reduction.fst1 by metis
  next
qed

```

```

lemma beta-reduces-snd:
  assumes  $P \rightarrow\beta^* P'$ 
  shows  $(Snd P) \rightarrow\beta^* (Snd P')$ 
using assms proof(induction)
  case (reflexive  $M$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (transitive  $M M' M''$ )
    thus ?case using beta-reduces.transitive beta-reduction.snd1 by metis
  next
qed

```

```

theorem preservation:
  assumes  $M \rightarrow\beta^* M' \Gamma \vdash M : \tau$ 
  shows  $\Gamma \vdash M' : \tau$ 
using assms proof(induction)
  case (reflexive  $M$ )
    thus ?case.
  next
  case (transitive  $M M' M''$ )
    thus ?case using preservation' by metis
  next
qed

```

```

theorem safety:
  assumes  $M \rightarrow\beta^* M' \Gamma \vdash M : \tau$ 
  shows  $NF M' \vee (\exists M''. (M' \rightarrow\beta M''))$ 
using assms proof(induction)
  case (reflexive  $M$ )
    thus ?case using progress by metis
  next
  case (transitive  $M M' M''$ )
    hence  $\Gamma \vdash M' : \tau$  using preservation by metis
    hence  $\Gamma \vdash M'' : \tau$  using preservation'  $\langle M' \rightarrow\beta M'' \rangle$  by metis
    thus ?case using progress by metis
  next
qed

```

```

inductive parallel-reduction :: 'a trm  $\Rightarrow$  'a trm  $\Rightarrow$  bool ( $- \gg -$ ) where
  refl:  $A \gg A$ 
| beta:  $\llbracket A \gg A'; B \gg B' \rrbracket \Longrightarrow (App (Fn x T A) B) \gg (A'[x ::= B'])$ 
| eta:  $A \gg A' \Longrightarrow (Fn x T A) \gg (Fn x T A')$ 
| app:  $\llbracket A \gg A'; B \gg B' \rrbracket \Longrightarrow (App A B) \gg (App A' B')$ 
| pair:  $\llbracket A \gg A'; B \gg B' \rrbracket \Longrightarrow (Pair A B) \gg (Pair A' B')$ 
| fst1:  $P \gg P' \Longrightarrow (Fst P) \gg (Fst P')$ 
| fst2:  $A \gg A' \Longrightarrow (Fst (Pair A B)) \gg A'$ 
| snd1:  $P \gg P' \Longrightarrow (Snd P) \gg (Snd P')$ 
| snd2:  $B \gg B' \Longrightarrow (Snd (Pair A B)) \gg B'$ 

```

```

lemma parallel-reduction-prm:
  assumes  $A \gg A'$ 
  shows  $(\pi \cdot A) \gg (\pi \cdot A')$ 
using assms
  apply induction
  apply (rule parallel-reduction.refl)
  apply (metis parallel-reduction.beta subst-prm trm-prm-simp(3, 4))
  apply (metis parallel-reduction.eta trm-prm-simp(4))
  apply (metis parallel-reduction.app trm-prm-simp(3))
  apply (metis parallel-reduction.pair trm-prm-simp(5))
  apply (metis parallel-reduction.fst1 trm-prm-simp(6))
  apply (metis parallel-reduction.fst2 trm-prm-simp(5, 6))
  apply (metis parallel-reduction.snd1 trm-prm-simp(7))
  apply (metis parallel-reduction.snd2 trm-prm-simp(5, 7))
done

```

```

lemma parallel-reduction-fvs:
  assumes  $A \gg A'$ 
  shows  $fvs A' \subseteq fvs A$ 
using assms proof(induction)
  case (refl A)
    thus ?case by auto
  next
  case (beta A A' B B' x T)
    have  $*: fvs (App (Fn x T A) B) = fvs A - \{x\} \cup fvs B$  using fvs-simp(3, 4)
  by metis
    have  $fvs (A'[x ::= B']) \subseteq fvs A' - \{x\} \cup fvs B'$  using subst-fvs.
    also have  $\dots \subseteq fvs A - \{x\} \cup fvs B$  using beta.IH by auto
    finally show ?case using fvs-simp(3, 4) by metis
  next
  case (eta A A' x T)
    thus ?case using fvs-simp(4) Un-Diff subset-Un-eq by metis
  next
  case (app A A' B B')
    thus ?case using fvs-simp(3) Un-mono by metis
  next
  case (pair A A' B B')
    thus ?case using fvs-simp(5) Un-mono by metis
  next
  case (fst1 P P')
    thus ?case using fvs-simp(6) by force
  next
  case (fst2 A A' B)
    thus ?case using fvs-simp(5, 6) by force
  next
  case (snd1 P P')
    thus ?case using fvs-simp(7) by force
  next
  case (snd2 B B' A)

```

```

    thus ?case using fvs-simp(5, 7) by force
  next
qed

inductive-cases parallel-reduction-unitE': Unit >> A
lemma parallel-reduction-unitE:
  assumes Unit >> A
  shows A = Unit
using assms
  apply (rule parallel-reduction-unitE'[where A=A])
  apply blast
  apply (auto simp add: unit-not-app unit-not-fn unit-not-pair unit-not-fst unit-not-snd)
done

inductive-cases parallel-reduction-varE': (Var x) >> A
lemma parallel-reduction-varE:
  assumes (Var x) >> A
  shows A = Var x
using assms
  apply (rule parallel-reduction-varE'[where x=x and A=A])
  apply blast
  apply (auto simp add: var-not-app var-not-fn var-not-pair var-not-fst var-not-snd)
done

inductive-cases parallel-reduction-fnE': (Fn x T A) >> X
lemma parallel-reduction-fnE:
  assumes (Fn x T A) >> X
  shows X = Fn x T A  $\vee$  ( $\exists A'$ . (A >> A')  $\wedge$  X = Fn x T A')
using assms proof(induction rule: parallel-reduction-fnE'[where x=x and T=T
and A=A and X=X])
  case (4 B B' y S)
  from this consider x = y  $\wedge$  T = S  $\wedge$  A = B | x  $\neq$  y  $\wedge$  T = S  $\wedge$  x  $\notin$  fvs B  $\wedge$ 
A = [x  $\leftrightarrow$  y]  $\cdot$  B
  using trm-simp(4) by metis
  thus ?case proof(cases)
    case 1
    hence x = y T = S A = B by auto
    thus ?thesis using 4 by metis
  next
  case 2
  hence x  $\neq$  y T = S x  $\notin$  fvs B A = [x  $\leftrightarrow$  y]  $\cdot$  B by auto
  hence x  $\notin$  fvs B' A >> ([x  $\leftrightarrow$  y]  $\cdot$  B')
  using parallel-reduction-fvs parallel-reduction-prm <B >> B' by auto
  thus ?thesis using fn-eq <X = Fn y S B'> <x  $\neq$  y> <T = S> by metis
  next
qed
next
qed (
  metis assms,

```

blast,
metis app-not-fn,
metis app-not-fn,
metis fn-not-pair,
metis fn-not-fst,
metis fn-not-fst,
metis fn-not-snd,
metis fn-not-snd
)

inductive-cases *parallel-reduction-redexE'*: $(App (Fn x T A) B) \gg X$

lemma *parallel-reduction-redexE*:

assumes $(App (Fn x T A) B) \gg X$

shows

$(X = App (Fn x T A) B) \vee$
 $(\exists A' B'. (A \gg A') \wedge (B \gg B') \wedge X = (A'[x ::= B'])) \vee$
 $(\exists A' B'. ((Fn x T A) \gg (Fn x T A')) \wedge (B \gg B') \wedge X = (App (Fn x T A') B'))$

using *assms proof*(*induction rule: parallel-reduction-redexE'*[**where** $x=x$ **and** $T=T$ **and** $A=A$ **and** $B=B$ **and** $X=X$])

case $(5 C C' D D')$

from $\langle App (Fn x T A) B = App C D \rangle$ **have** $C: C = Fn x T A$ **and** $D: D = B$

by (*metis trm-simp(2)*, *metis trm-simp(3)*)

from C **and** $\langle C \gg C' \rangle$ **obtain** A' **where** $C': C' = Fn x T A'$

using *parallel-reduction-fnE* **by** *metis*

thus *?thesis using* $C C' D \langle C \gg C' \rangle \langle D \gg D' \rangle \langle X = App C' D' \rangle$ **by** *metis*

next

case $(3 C C' D D' y S)$

from $\langle App (Fn x T A) B = App (Fn y S C) D \rangle$ **have** $Fn x T A = Fn y S C$ **and** $B: B = D$

by (*metis trm-simp(2)*, *metis trm-simp(3)*)

from *this* **consider**

$x = y \wedge T = S \wedge A = C$

$| x \neq y \wedge T = S \wedge A = [x \leftrightarrow y] \cdot C \wedge x \notin fvs C$

using *trm-simp(4)* **by** *metis*

thus *?case proof*(*cases*)

case 1

thus *?thesis using* $\langle C \gg C' \rangle \langle X = (C'[y ::= D']) \rangle \langle D \gg D' \rangle B$ **by** *metis*

next

case 2

hence $x \neq y T = S$ **and** $A: A = [x \leftrightarrow y] \cdot C \wedge x \notin fvs C$ **by** *auto*

have $x \notin fvs C'$ **using** *parallel-reduction-fvs* $\langle x \notin fvs C \rangle \langle C \gg C' \rangle$ **by**

force

have $A \gg ([x \leftrightarrow y] \cdot C')$

using *parallel-reduction-prm* $\langle C \gg C' \rangle A$ **by** *metis*

moreover **have** $X = (([x \leftrightarrow y] \cdot C')[x ::= D'])$

using $\langle X = (C'[y ::= D']) \rangle$ *subst-swp* $\langle x \notin fvs C' \rangle$ **by** *metis*

```

      ultimately show ?thesis using ‹D >> D'› B by metis
    next
    qed
  next
  qed (
    metis assms,
    blast,
    metis app-not-fn,
    metis app-not-pair,
    metis app-not-fst,
    metis app-not-fst,
    metis app-not-snd,
    metis app-not-snd
  )

  inductive-cases parallel-reduction-nonredexE': (App A B) >> X
  lemma parallel-reduction-nonredexE:
    assumes (App A B) >> X and  $\bigwedge x T A'. A \neq \text{Fn } x T A'$ 
    shows  $\exists A' B'. (A >> A') \wedge (B >> B') \wedge X = (\text{App } A' B')$ 
  using assms proof(induction rule: parallel-reduction-nonredexE'[where A=A and
  B=B and X=X])
    case (5 C C' D D')
      hence  $A = C B = D$  using trm-simp(2, 3) by auto
      thus ?case using ‹C >> C'› ‹D >> D'› ‹X = App C' D'› by metis
    next
  qed (
    metis assms(1),
    metis parallel-reduction.refl,
    metis trm-simp(2, 3) assms(2),
    metis app-not-fn,
    metis app-not-pair,
    metis app-not-fst,
    metis app-not-fst,
    metis app-not-snd,
    metis app-not-snd
  )

  inductive-cases parallel-reduction-pairE': (Pair A B) >> X
  lemma parallel-reduction-pairE:
    assumes (Pair A B) >> X
    shows  $\exists A' B'. (A >> A') \wedge (B >> B') \wedge (X = \text{Pair } A' B')$ 
  using assms proof(induction rule: parallel-reduction-pairE'[where A=A and B=B
  and X=X])
    case 2
      thus ?case using parallel-reduction.refl by blast
    next
    case (6 A A' B B')
      thus ?case using parallel-reduction.pair trm-simp(5, 6) by fastforce
    next

```

```

qed (
  metis assms,
  metis app-not-pair,
  metis fn-not-pair,
  metis app-not-pair,
  metis pair-not-fst,
  metis pair-not-fst,
  metis pair-not-snd,
  metis pair-not-snd
)

inductive-cases parallel-reduction-fstE': (Fst P) >> X
lemma parallel-reduction-fstE:
  assumes (Fst P) >> X
  shows ( $\exists P'. (P \gg P') \wedge X = (Fst P')$ )  $\vee$  ( $\exists A A' B. (P = Pair A B) \wedge (A \gg A') \wedge X = A'$ )
using assms proof(induction rule: parallel-reduction-fstE'[where P=P and X=X])
  case ( $\gamma P P'$ )
    thus ?case using parallel-reduction.fst1 trm-simp( $\gamma$ ) by metis
  next
  case ( $\delta A B$ )
    thus ?case using parallel-reduction.fst2 trm-simp( $\gamma$ ) by metis
  next
qed (
  metis assms,
  insert parallel-reduction.refl, metis,
  metis app-not-fst,
  metis fn-not-fst,
  metis app-not-fst,
  metis pair-not-fst,
  metis fst-not-snd,
  metis fst-not-snd
)

inductive-cases parallel-reduction-sndE': (Snd P) >> X
lemma parallel-reduction-sndE:
  assumes (Snd P) >> X
  shows ( $\exists P'. (P \gg P') \wedge X = (Snd P')$ )  $\vee$  ( $\exists A B B'. (P = Pair A B) \wedge (B \gg B') \wedge X = B'$ )
using assms proof(induction rule: parallel-reduction-sndE'[where P=P and X=X])
  case ( $\gamma P P'$ )
    thus ?case using parallel-reduction.snd1 trm-simp( $\delta$ ) by metis
  next
  case ( $\delta A B$ )
    thus ?case using parallel-reduction.snd2 trm-simp( $\delta$ ) by metis
  next
qed (
  metis assms,
  insert parallel-reduction.refl, metis,

```

```

metis app-not-snd,
metis fn-not-snd,
metis app-not-snd,
metis pair-not-snd,
metis fst-not-snd,
metis fst-not-snd
)

```

lemma *parallel-reduction-subst-inner*:

```

assumes  $M \gg M'$ 
shows  $X[z ::= M] \gg (X[z ::= M'])$ 
using assms proof(induction  $X$  rule: trm-strong-induct[where  $S = \{z\} \cup fvs M \cup fvs M'$ ])
show finite ( $\{z\} \cup fvs M \cup fvs M'$ ) using fvs-finite by auto

```

```

case 1
  thus ?case using subst-simp-unit parallel-reduction.refl by metis
next
case (2  $x$ )
  thus ?case by(cases  $x = z$ , metis subst-simp-var1, metis subst-simp-var2 parallel-reduction.refl)
next
case (3  $A B$ )
  thus ?case using subst-simp-app parallel-reduction.app by metis
next
case (4  $x T A$ )
  hence  $x \neq z$   $x \notin fvs M$   $x \notin fvs M'$  by auto
  thus ?case using 4 subst-simp-fn parallel-reduction.eta by metis
next
case (5  $A B$ )
  thus ?case using subst-simp-pair parallel-reduction.pair by metis
next
case (6  $P$ )
  thus ?case using subst-simp-fst parallel-reduction.fst1 by metis
next
case (7  $P$ )
  thus ?case using subst-simp-snd parallel-reduction.snd1 by metis
next
qed

```

lemma *parallel-reduction-subst*:

```

assumes  $X \gg X'$   $M \gg M'$ 
shows  $X[z ::= M] \gg (X'[z ::= M'])$ 
using assms proof(induction  $X$  arbitrary:  $X'$  rule: trm-strong-depth-induct[where  $S = \{z\} \cup fvs M \cup fvs M'$ ])
show finite ( $\{z\} \cup fvs M \cup fvs M'$ ) using fvs-finite by auto
next

```

```

case 1

```

hence $X' = \text{Unit}$ **using** *parallel-reduction-unitE* **by** *metis*
 thus $?case$ **using** *parallel-reduction.refl subst-simp-unit* **by** *metis*
 next
 case (2 x)
 hence $X' = \text{Var } x$ **using** *parallel-reduction-varE* **by** *metis*
 thus $?case$ **using** *parallel-reduction-subst-inner* $\langle M \gg M' \rangle$ **by** *metis*
 next
 case (3 $C D$)
 consider $\exists x T A. C = \text{Fn } x T A \mid \nexists x T A. C = \text{Fn } x T A$ **by** *metis*
 thus $?case$ **proof**(*cases*)
 case 1
 from *this* **obtain** $x T A$ **where** $C: C = \text{Fn } x T A$ **by** *auto*
 have $\text{depth } C < \text{depth } (\text{App } C D)$ $\text{depth } D < \text{depth } (\text{App } C D)$
 using *depth-app* **by** *auto*

 consider
 $X' = \text{App } (\text{Fn } x T A) D$
 $\mid \exists A' D'. ((\text{Fn } x T A) \gg (\text{Fn } x T A')) \wedge (D \gg D') \wedge X' = (\text{App } (\text{Fn } x T A') D')$
 $\mid \exists A' D'. (A \gg A') \wedge (D \gg D') \wedge X' = (A[x ::= D'])$
using *parallel-reduction-redexE* $\langle (\text{App } C D) \gg X' \rangle C$ **by** *metis*
thus $?thesis$ **proof**(*cases*)
 case 1
thus $?thesis$ **using** *parallel-reduction-subst-inner* $\langle M \gg M' \rangle C$ **by** *metis*
 next
 case 2
 from *this* **obtain** $A' D'$
where $(\text{Fn } x T A) \gg (\text{Fn } x T A') D \gg D'$ **and** $X': X' = \text{App } (\text{Fn } x T A') D'$
by *auto*
have $*$: $((\text{Fn } x T A)[z ::= M]) \gg ((\text{Fn } x T A')[z ::= M'])$
using $\exists.IH$ $\langle \text{depth } C < \text{depth } (\text{App } C D) \rangle C \langle (\text{Fn } x T A) \gg (\text{Fn } x T A') \rangle \langle M \gg M' \rangle$
by *metis*
have $**$: $(D[z ::= M]) \gg (D'[z ::= M'])$
using $\exists.IH$ $\langle \text{depth } D < \text{depth } (\text{App } C D) \rangle \langle D \gg D' \rangle \langle M \gg M' \rangle$
by *metis*

have $(\text{App } C D)[z ::= M] = \text{App } ((\text{Fn } x T A)[z ::= M]) (D[z ::= M])$
using *subst-simp-app* C **by** *metis*
moreover **have** $\dots \gg (\text{App } ((\text{Fn } x T A')[z ::= M']) (D'[z ::= M']))$
using $*$ $**$ *parallel-reduction.app* **by** *metis*
moreover **have** $\dots = ((\text{App } (\text{Fn } x T A') D')[z ::= M'])$
using *subst-simp-app* **by** *metis*
moreover **have** $\dots = (X'[z ::= M'])$
using X' **by** *metis*
ultimately show $?thesis$ **by** *metis*
 next
 case 3

```

from this obtain  $A' D'$  where  $A \gg A' D \gg D'$  and  $X': X' = (A'[x$ 
 $::= D']$ )
  by auto

  have  $\text{depth } A < \text{depth } (\text{App } C D)$ 
    using  $C \text{ depth-app depth-fn dual-order.strict-trans}$  by fastforce

  have  $\text{finite } (\{z\} \cup \text{fvs } M \cup \text{fvs } M' \cup \text{fvs } A')$  using fvs-finite by auto
  from this obtain  $y$ 
    where  $y \notin \{z\} \cup \text{fvs } M \cup \text{fvs } M' \cup \text{fvs } A'$  and  $C: C = \text{Fn } y T ([y \leftrightarrow$ 
 $x] \cdot A)$ 
    using fresh-fn  $C$  by metis
    hence  $y \neq z \ y \notin \text{fvs } M \ y \notin \text{fvs } M' \ y \notin \text{fvs } A'$  by auto
    have  $([y \leftrightarrow x] \cdot A) \gg ([y \leftrightarrow x] \cdot A')$  using parallel-reduction-prm  $\langle A$ 
 $\gg A' \rangle$  by metis
    hence  $*$ :  $([y \leftrightarrow x] \cdot A)[z ::= M] \gg (([y \leftrightarrow x] \cdot A')[z ::= M'])$ 
      using  $\exists.IH \langle \text{depth } A < \text{depth } (\text{App } C D) \rangle \text{ depth-prm}$ 
      using  $\langle ([y \leftrightarrow x] \cdot A) \gg ([y \leftrightarrow x] \cdot A') \rangle \langle M \gg M' \rangle$  by metis
    have  $**$ :  $(D[z ::= M]) \gg (D'[z ::= M'])$ 
      using  $\exists.IH \langle \text{depth } D < \text{depth } (\text{App } C D) \rangle \langle D \gg D' \rangle \langle M \gg M' \rangle$ 
      by metis

    have  $(\text{App } C D)[z ::= M] = (\text{App } ((\text{Fn } y T ([y \leftrightarrow x] \cdot A)))[z ::= M])$ 
 $(D[z ::= M])$ 
      using  $C \text{ subst-simp-app}$  by metis
    moreover have  $\dots = (\text{App } (\text{Fn } y T (([y \leftrightarrow x] \cdot A)[z ::= M])) (D[z ::=$ 
 $M]))$ 
      using  $\langle y \neq z \rangle \langle y \notin \text{fvs } M \rangle \text{ subst-simp-fn}$  by metis
    moreover have  $\dots \gg (([y \leftrightarrow x] \cdot A')[z ::= M'] [y ::= D'[z ::= M']])$ 
      using parallel-reduction.beta * ** by metis
    moreover have  $\dots = (([y \leftrightarrow x] \cdot A')[y ::= D'] [z ::= M'])$ 
      using barendregt  $\langle y \neq z \rangle \langle y \notin \text{fvs } M' \rangle$  by metis
    moreover have  $\dots = (A'[x ::= D'] [z ::= M'])$ 
      using subst-swp  $\langle y \notin \text{fvs } A' \rangle$  by metis
    moreover have  $\dots = (X'[z ::= M'])$  using  $X'$  by metis
    ultimately show  $?thesis$  by metis
  next
  qed
next
case 2
from this obtain  $C' D'$  where  $C \gg C' D \gg D'$  and  $X': X' = \text{App } C'$ 
 $D'$ 
  using parallel-reduction-nonredexE  $\langle (\text{App } C D) \gg X' \rangle$  by metis

  have  $\text{depth } C < \text{depth } (\text{App } C D) \ \text{depth } D < \text{depth } (\text{App } C D)$ 
    using depth-app by auto
  hence  $*$ :  $(C[z ::= M]) \gg (C'[z ::= M'])$  and  $**$ :  $(D[z ::= M]) \gg (D'[z$ 
 $::= M'])$ 
    using  $\exists.IH \langle C \gg C' \rangle \langle D \gg D' \rangle \langle M \gg M' \rangle$  by metis+

```

have $(App\ C\ D)[z ::= M] = App\ (C[z ::= M])\ (D[z ::= M])$
using *subst-simp-app* **by** *metis*
moreover have $\dots \gg (App\ (C'[z ::= M'])\ (D'[z ::= M']))$
using *parallel-reduction.app * *** **by** *metis*
moreover have $\dots = ((App\ C'\ D')[z ::= M'])$
using *subst-simp-app* **by** *metis*
moreover have $\dots = (X'[z ::= M'])$ **using** X' **by** *metis*
ultimately show *?thesis* **by** *metis*
next
qed
next
case $(\not\vdash x\ T\ A)$
hence $x \neq z\ x \notin fvs\ M\ x \notin fvs\ M'$
by *auto*

from $\langle Fn\ x\ T\ A \rangle \gg X'$ **consider**
 $X' = Fn\ x\ T\ A$
 $|\ \exists A'. (A \gg A') \wedge X' = Fn\ x\ T\ A'$ **using** *parallel-reduction-fnE* **by** *metis*
thus *?case proof(cases)*
case 1
thus *?thesis* **using** *parallel-reduction-subst-inner* $\langle M \gg M' \rangle$ **by** *metis*
next
case 2
from *this* **obtain** A' **where** $A \gg A'$ **and** $X': X' = Fn\ x\ T\ A'$ **by** *auto*

hence $\ast: (A[z ::= M]) \gg (A'[z ::= M'])$
using 4.IH *depth-fn* $\langle A \gg A' \rangle \langle M \gg M' \rangle$ **by** *metis*

have $((Fn\ x\ T\ A)[z ::= M]) = (Fn\ x\ T\ (A[z ::= M]))$
using *subst-simp-fn* $\langle x \neq z \rangle \langle x \notin fvs\ M \rangle$ **by** *metis*
moreover have $\dots \gg (Fn\ x\ T\ (A'[z ::= M']))$
using *parallel-reduction.eta * *** **by** *metis*
moreover have $\dots = ((Fn\ x\ T\ A')[z ::= M'])$
using *subst-simp-fn* $\langle x \neq z \rangle \langle x \notin fvs\ M' \rangle$ **by** *metis*
moreover have $\dots = (X'[z ::= M'])$
using X' **by** *metis*
ultimately show *?thesis* **by** *metis*
next
qed
next
case $(\not\vdash A\ B)$
from $\langle Pair\ A\ B \rangle \gg X'$ **consider**
 $X' = Pair\ A\ B$
 $|\ \exists A'\ B'. (A \gg A') \wedge (B \gg B') \wedge X' = Pair\ A'\ B'$
using *parallel-reduction-pairE* **by** *metis*
thus *?case proof(cases)*
case 1
thus *?thesis* **using** *parallel-reduction-subst-inner* $\langle M \gg M' \rangle$ **by** *metis*

```

next
case 2
  from this obtain A' B' where A >> A' B >> B' and X': X' = Pair A'
  B' by auto

  have *: (A[z ::= M]) >> (A'[z ::= M']) and **: (B[z ::= M]) >> (B'[z
  ::= M'])
  using 5.IH ⟨A >> A'⟩ ⟨B >> B'⟩ ⟨M >> M'⟩ by (metis depth-pair(1),
  metis depth-pair(2))

  have (Pair A B)[z ::= M] = (Pair (A[z ::= M]) (B[z ::= M]))
  using subst-simp-pair by metis
  moreover have ... >> (Pair (A'[z ::= M']) (B'[z ::= M']))
  using parallel-reduction.pair * ** by metis
  moreover have ... = ((Pair A' B')[z ::= M'])
  using subst-simp-pair by metis
  moreover have ... = (X'[z ::= M']) using X' by metis
  ultimately show ?thesis by metis
next
qed
next
case (6 P)
  from ⟨Fst P⟩ >> X' consider
  ∃ P'. (P >> P') ∧ X' = Fst P'
  | ∃ A A' B. P = Pair A B ∧ (A >> A') ∧ X' = A'
  using parallel-reduction-fstE by metis
  thus ?case proof(cases)
  case 1
    from this obtain P' where P >> P' and X': X' = Fst P' by auto

    have *: (P[z ::= M]) >> (P'[z ::= M'])
    using 6.IH depth-fst ⟨P >> P'⟩ ⟨M >> M'⟩ by metis

    have (Fst P)[z ::= M] = Fst (P[z ::= M])
    using subst-simp-fst by metis
    moreover have ... >> (Fst (P'[z ::= M']))
    using parallel-reduction.fst1 * by metis
    moreover have ... = ((Fst P')[z ::= M'])
    using subst-simp-fst by metis
    moreover have ... = (X'[z ::= M']) using X' by metis
    ultimately show ?thesis by metis
  next
  case 2
    from this obtain A A' B where P: P = Pair A B A >> A' and X': X'
    = A' by auto

    have depth A < depth (Fst P)
    using P depth-fst depth-pair dual-order.strict-trans by fastforce
    hence *: (A[z ::= M]) >> (A'[z ::= M'])

```

```

    using 6.IH  $\langle A \gg A' \rangle \langle M \gg M' \rangle$  by metis

  have (Fst P)[z ::= M] = (Fst (Pair (A[z ::= M]) (B[z ::= M])))
    using P subst-simp-fst subst-simp-pair by metis
  moreover have ...  $\gg (A'[z ::= M'])$ 
    using parallel-reduction.fst2 * by metis
  moreover have ... = (X'[z ::= M'])
    using X' by metis
  ultimately show ?thesis by metis
next
qed
next
case ( $\gamma$  P)
  from  $\langle (Snd P) \gg X' \rangle$  consider
     $\exists P'. (P \gg P') \wedge X' = Snd P'$ 
  |  $\exists A B B'. P = Pair A B \wedge (B \gg B') \wedge X' = B'$ 
    using parallel-reduction-sndE by metis
  thus ?case proof(cases)
  case 1
    from this obtain P' where  $P \gg P'$  and  $X': X' = Snd P'$  by auto

    have *: (P[z ::= M])  $\gg (P'[z ::= M'])$ 
      using 7.IH depth-snd  $\langle P \gg P' \rangle \langle M \gg M' \rangle$  by metis

    have (Snd P)[z ::= M] = Snd (P[z ::= M])
      using subst-simp-snd by metis
    moreover have ...  $\gg (Snd (P'[z ::= M']))$ 
      using parallel-reduction.snd1 * by metis
    moreover have ... = ((Snd P')[z ::= M'])
      using subst-simp-snd by metis
    moreover have ... = (X'[z ::= M']) using X' by metis
    ultimately show ?thesis by metis
  next
  case 2
    from this obtain A B B' where  $P: P = Pair A B B \gg B'$  and  $X': X' = B'$  by auto

    have depth B < depth (Snd P)
      using P depth-snd depth-pair dual-order.strict-trans by fastforce
    hence *: (B[z ::= M])  $\gg (B'[z ::= M'])$ 
      using 7.IH  $\langle B \gg B' \rangle \langle M \gg M' \rangle$  by metis

    have (Snd P)[z ::= M] = (Snd (Pair (A[z ::= M]) (B[z ::= M])))
      using P subst-simp-snd subst-simp-pair by metis
    moreover have ...  $\gg (B'[z ::= M'])$ 
      using parallel-reduction.snd2 * by metis
    moreover have ... = (X'[z ::= M'])
      using X' by metis
    ultimately show ?thesis by metis

```

next
qed
next
qed

inductive complete-development :: 'a trm \Rightarrow 'a trm \Rightarrow bool (- >>> -) **where**
unit: Unit >>> Unit
| *var*: (Var x) >>> (Var x)
| *beta*: $\llbracket A >>> A'; B >>> B' \rrbracket \Longrightarrow (App (Fn x T A) B) >>> (A'[x ::= B'])$
| *eta*: $A >>> A' \Longrightarrow (Fn x T A) >>> (Fn x T A')$
| *app*: $\llbracket A >>> A'; B >>> B'; (\bigwedge x T M. A \neq Fn x T M) \rrbracket \Longrightarrow (App A B) >>> (App A' B')$
| *pair*: $\llbracket A >>> A'; B >>> B' \rrbracket \Longrightarrow (Pair A B) >>> (Pair A' B')$
| *fst1*: $\llbracket P >>> P'; (\bigwedge A B. P \neq Pair A B) \rrbracket \Longrightarrow (Fst P) >>> (Fst P')$
| *fst2*: $A >>> A' \Longrightarrow (Fst (Pair A B)) >>> A'$
| *snd1*: $\llbracket P >>> P'; (\bigwedge A B. P \neq Pair A B) \rrbracket \Longrightarrow (Snd P) >>> (Snd P')$
| *snd2*: $B >>> B' \Longrightarrow (Snd (Pair A B)) >>> B'$

lemma not-fn-prm:

assumes $\bigwedge x T M. A \neq Fn x T M$
shows $\pi \cdot A \neq Fn x T M$

proof(rule classical)

fix x T M

obtain π' **where** *: $\pi' = prm-inv \pi$ **by** auto

assume $\neg(\pi \cdot A \neq Fn x T M)$

hence $\pi \cdot A = Fn x T M$ **by** blast

hence $\pi' \cdot (\pi \cdot A) = \pi' \cdot Fn x T M$ **by** fastforce

hence $(\pi' \diamond \pi) \cdot A = \pi' \cdot Fn x T M$

using trm-prm-apply-compose **by** metis

hence $A = \pi' \cdot Fn x T M$

using * prm-inv-compose trm-prm-apply-id **by** metis

hence $A = Fn (\pi' \$ x) T (\pi' \cdot M)$ **using** trm-prm-simp(4) **by** metis

hence False **using** assms **by** blast

thus ?thesis **by** blast

qed

lemma not-pair-prm:

assumes $\bigwedge A B. P \neq Pair A B$

shows $\pi \cdot P \neq Pair A B$

proof(rule classical)

fix A B

obtain π' **where** *: $\pi' = prm-inv \pi$ **by** auto

assume $\neg(\pi \cdot P \neq Pair A B)$

hence $\pi \cdot P = Pair A B$ **by** blast

hence $\pi' \cdot \pi \cdot P = \pi' \cdot (Pair A B)$ **by** fastforce

hence $(\pi' \diamond \pi) \cdot P = \pi' \cdot (Pair A B)$

using trm-prm-apply-compose **by** metis

hence $P = \pi' \cdot (Pair A B)$

using * prm-inv-compose trm-prm-apply-id **by** metis

```

    hence  $P = \text{Pair } (\pi' \cdot A) (\pi' \cdot B)$  using trm-prm-simp(5) by metis
    hence False using assms by blast
    thus ?thesis by blast
qed

lemma complete-development-prm:
  assumes  $A \ggg A'$ 
  shows  $(\pi \cdot A) \ggg (\pi \cdot A')$ 
using assms proof(induction)
  case unit
    thus ?case using complete-development.unit trm-prm-simp(1) by metis
  next
  case (var x)
    thus ?case using complete-development.var trm-prm-simp(2) by metis
  next
  case (beta A A' B B' x T)
    thus ?case using complete-development.beta subst-prm trm-prm-simp(3, 4) by
metis
  next
  case (eta A A' x T)
    thus ?case using complete-development.eta trm-prm-simp(4) by metis
  next
  case (app A A' B B')
    thus ?case using complete-development.app by (simp add: trm-prm-simp(3))
not-fn-prm)
  next
  case (pair A A' B B')
    thus ?case using complete-development.pair trm-prm-simp(5) by metis
  next
  case (fst1 P P')
    hence  $\pi \cdot P \neq \text{Pair } A B$  for  $A B$  using not-pair-prm by metis
    thus ?case using trm-prm-simp(6) fst1.IH complete-development.fst1 by metis
  next
  case (fst2 A A' B)
    thus ?case using trm-prm-simp(5, 6) complete-development.fst2 by metis
  next
  case (snd1 P P')
    hence  $\pi \cdot P \neq \text{Pair } A B$  for  $A B$  using not-pair-prm by metis
    thus ?case using trm-prm-simp(7) snd1.IH complete-development.snd1 by
metis
  next
  case (snd2 B B' A)
    thus ?case using trm-prm-simp(5, 7) complete-development.snd2 by metis
  next
qed

lemma complete-development-fvs:
  assumes  $A \ggg A'$ 
  shows  $\text{fvs } A' \subseteq \text{fvs } A$ 

```

```

using assms proof(induction)
  case unit
    thus ?case using fvs-simp by auto
  next
  case (var x)
    thus ?case using fvs-simp by auto
  next
  case (beta A A' B B' x T)
    have  $fvs(A'[x ::= B']) \subseteq fvs A' - \{x\} \cup fvs B'$  using subst-fvs.
    also have  $\dots \subseteq fvs A - \{x\} \cup fvs B$  using beta.IH by auto
    also have  $\dots \subseteq fvs (Fn\ x\ T\ A) \cup fvs B$  using fvs-simp(4) subset-refl by force
    also have  $\dots \subseteq fvs (App\ (Fn\ x\ T\ A)\ B)$  using fvs-simp(3) subset-refl by force
    finally show ?case.
  next
  case (eta A A' x T)
    thus ?case using fvs-simp(4) using Un-Diff subset-Un-eq by (metis (no-types,
lifting))
  next
  case (app A A' B B')
    thus ?case using fvs-simp(3) Un-mono by metis
  next
  case (pair A A' B B')
    thus ?case using fvs-simp(5) Un-mono by metis
  next
  case (fst1 P P')
    thus ?case using fvs-simp(6) by force
  next
  case (fst2 A A' B)
    thus ?case by (simp add: fvs-simp(5, 6) sup.coboundedI1)
  next
  case (snd1 P P')
    thus ?case using fvs-simp(7) by fastforce
  next
  case (snd2 B B' A)
    thus ?case using fvs-simp(5, 7) by fastforce
  next
qed

```

lemma *complete-development-fnE*:

assumes $(Fn\ x\ T\ A) \gg \gg X$

shows $\exists A'. (A \gg \gg A') \wedge X = Fn\ x\ T\ A'$

using *assms* **proof**(*cases*)

case (*eta* *B* *B'* *y* *S*)

hence $T = S$ **using** *trm-simp(4)* **by** *metis*

from *eta* **consider** $x = y \wedge A = B \mid x \neq y \wedge x \notin fvs B \wedge A = [x \leftrightarrow y] \cdot B$

using *trm-simp(4)* **by** *metis*

thus ?*thesis* **proof**(*cases*)

case *1*

hence $x = y$ **and** $A = B$ **by** *auto*

```

    obtain A' where A' = B' by auto
    hence A >>> A' and X = Fn x T A' using eta ⟨A = B⟩ ⟨x = y⟩ ⟨T =
S⟩ by auto
    thus ?thesis by auto
  next
  case 2
  hence x ≠ y x ∉ fvs B and A: A = [x ↔ y] · B by auto
  hence x ∉ fvs B' using ⟨B >>> B'⟩ complete-development-fvs by auto
  obtain A' where A': A' = [x ↔ y] · B' by auto
  hence A >>> A' using A ⟨B >>> B'⟩ complete-development-prm by auto
  have X = Fn x T A'
    using fn-eq ⟨x ≠ y⟩ ⟨x ∉ fvs B'⟩ A' ⟨X = Fn y S B'⟩ ⟨T = S⟩ by metis
  thus ?thesis using ⟨A >>> A'⟩ by auto
  next
  qed
  next
  qed (
    metis unit-not-fn,
    metis var-not-fn,
    metis app-not-fn,
    metis app-not-fn,
    metis fn-not-pair,
    metis fn-not-fst,
    metis fn-not-fst,
    metis fn-not-snd,
    metis fn-not-snd
  )

```

```

lemma complete-development-pairE:
  assumes (Pair A B) >>> X
  shows ∃ A' B'. (A >>> A') ∧ (B >>> B') ∧ X = Pair A' B'
using assms
  apply cases
  apply (metis unit-not-pair, metis var-not-pair, metis app-not-pair, metis fn-not-pair,
metis app-not-pair)
  apply (metis trm-simp(5, 6))
  apply (metis pair-not-fst, metis pair-not-fst, metis pair-not-snd, metis pair-not-snd)
done

```

```

lemma complete-development-exists:
  shows ∃ X. (A >>> X)
proof(induction A rule: trm-induct)
  case 1
  obtain X :: 'a trm where X = Unit by auto
  hence Unit >>> X using complete-development.unit by metis
  thus ?case by auto
  next
  case (2 x)
  obtain X where X = Var x by auto

```

```

    hence (Var x) >>> X using complete-development.var by metis
  thus ?case by auto
next
case (3 A B)
  from this obtain A' B' where A': A >>> A' and B': B >>> B' by auto
  consider (∃ x T M. A = Fn x T M) | ¬(∃ x T M. A = Fn x T M) by auto
  thus ?case proof(cases)
    case 1
      from this obtain x T M where A: A = Fn x T M by auto
      from this obtain M' where A' = Fn x T M' and M >>> M'
        using complete-development.fnE A' by metis
      obtain X where X = (M[x ::= B']) by auto
      hence (App A B) >>> X
        using complete-development.beta ⟨M >>> M'⟩ B' A by metis
      thus ?thesis by auto
    next
    case 2
      thus ?thesis using complete-development.app A' B' by metis
    next
  qed
next
case (4 x T A)
  from this obtain A' where A': A >>> A' by auto
  obtain X where X = Fn x T A' by auto
  hence (Fn x T A) >>> X using complete-development.eta A' by metis
  thus ?case by auto
next
case (5 A B)
  thus ?case using complete-development.pair by blast
next
case (6 P)
  consider ∃ A B. P = Pair A B | ∄ A B. P = Pair A B by auto
  thus ?case proof(cases)
    case 1
      from this obtain A B X where P = Pair A B P >>> X using 6 by auto
      from this obtain A' B' where A >>> A' B >>> B' X = Pair A' B'
        using complete-development.pairE by metis
      thus ?thesis using complete-development.fst2 ⟨P = Pair A B⟩ by metis
    next
    case 2
      thus ?thesis using complete-development.fst1 6 by blast
    next
  qed
next
case (7 P)
  consider ∃ A B. P = Pair A B | ∄ A B. P = Pair A B by auto
  thus ?case proof(cases)
    case 1
      from this obtain A B X where P = Pair A B P >>> X using 7 by auto

```

```

    from this obtain A' B' where A >>> A' B >>> B' X = Pair A' B'
      using complete-development-pairE by metis
    thus ?thesis using complete-development.snd2 ⟨P = Pair A B⟩ by metis
  next
  case 2
    thus ?thesis using complete-development.snd1 7 by blast
  next
  qed
next
qed

lemma complete-development-triangle:
  assumes A >>> D A >> B
  shows B >> D
using assms proof(induction arbitrary: B rule: complete-development.induct)
  case unit
    thus ?case using parallel-reduction-unitE parallel-reduction.refl by metis
  next
  case (var x)
    thus ?case using parallel-reduction-varE parallel-reduction.refl by metis
  next
  case (beta A A' C C' x T)
    hence A >> A' C >> C' using parallel-reduction.refl by metis+
    from ⟨(App (Fn x T A) C) >> B⟩ consider
      B = App (Fn x T A) C
      | ∃ A'' C''. (A >> A'') ∧ (C >> C'') ∧ B = (A''[x ::= C''])
      | ∃ A'' C''. ((Fn x T A) >> (Fn x T A'')) ∧ (C >> C'') ∧ B = (App (Fn x
T A'') C'')
    using parallel-reduction-redexE by metis
    thus ?case proof(cases)
      case 1
        thus ?thesis using parallel-reduction.beta ⟨A >> A'⟩ ⟨C >> C'⟩ by metis
      next
      case 2
        from this obtain A'' C'' where A >> A'' C >> C'' and B: B = (A''[x
::= C'']) by auto
        hence A'' >> A' C'' >> C' using beta.IH by metis+
        thus ?thesis using B parallel-reduction-subst by metis
      next
      case 3
        from this obtain A'' C''
          where (Fn x T A) >> (Fn x T A'') C >> C'' and B: B = App (Fn x T
A'') C''
          by auto
        hence C'' >> C' using beta.IH by metis
        have A'' >> A'
        proof -
          thm parallel-reduction-fnE
          from ⟨(Fn x T A) >> (Fn x T A'')⟩ consider

```

```

       $F_n x T A = F_n x T A''$ 
    |  $\exists A''' . (A \gg A''') \wedge F_n x T A'' = F_n x T A'''$ 
      using parallel-reduction-fnE by metis
    hence  $A \gg A''$  proof(cases)
    case 1
      hence  $A = A''$  using trm-simp(4) by metis
      thus ?thesis using parallel-reduction.refl by metis
    next
    case 2
      from this obtain  $A'''$  where  $A \gg A'''$   $F_n x T A'' = F_n x T A'''$  by
auto
      thus ?thesis using trm-simp(4) by metis
    next
    qed
    thus ?thesis using beta.IH by metis
  qed
  thus ?thesis using  $B \langle C'' \gg C' \rangle$  parallel-reduction.beta by metis
next
qed
next
case (eta  $A A' x T B$ )
  from this consider
     $B = F_n x T A$ 
  |  $\exists A'' . (A \gg A'') \wedge B = F_n x T A''$  using parallel-reduction-fnE by metis
  thus ?case proof(cases)
    case 1
      thus ?thesis using eta.IH parallel-reduction.refl parallel-reduction.eta by
metis
    next
    case 2
      from this obtain  $A''$  where  $A \gg A''$  and  $B = F_n x T A''$  by auto
      thus ?thesis using eta.IH parallel-reduction.eta by metis
    next
    qed
  next
  case (app  $A A' C C'$ )
    from this obtain  $A'' C''$  where  $A \gg A''$   $C \gg C''$  and  $B: B = App A''$ 
C''
    using parallel-reduction-nonredexE by metis
    hence  $A'' \gg A' C'' \gg C'$  using app.IH by metis+
    thus ?case using  $B$  parallel-reduction.app by metis
  next
  case (pair  $A A' C C'$ )
    from  $\langle (Pair A C) \gg B \rangle$  and parallel-reduction-pairE obtain  $A'' C''$  where
 $A \gg A''$   $C \gg C''$   $B = Pair A'' C''$  by metis
    thus ?case using pair.IH parallel-reduction.pair by metis
  next
  case (fst1  $P P'$ )
    from this obtain  $P''$  where  $P \gg P''$   $B = Fst P''$ 

```

```

    using parallel-reduction-fstE by blast
  thus ?case using fst1.IH parallel-reduction.fst1 by metis
next
case (fst2 A A' C B)
  from this consider
     $\exists P''. ((Pair\ A\ C) \gg P'') \wedge B = Fst\ P''$ 
  |  $\exists A''. (A \gg A'') \wedge (B = A'')$ 
  using parallel-reduction-fstE[where  $P=(Pair\ A\ C)$  and  $X=B$ ] using trm-simp(5)
by metis
  thus ?case proof(cases)
    case 1
      from this obtain  $P''$  where  $(Pair\ A\ C) \gg P''$  and  $B = Fst\ P''$  by auto
      from this obtain  $A''\ C''$  where  $P'' = Pair\ A''\ C''$   $A \gg A''\ C \gg C''$ 
        using parallel-reduction-pairE by metis
      thus ?thesis using fst2 parallel-reduction.fst2  $\langle B = Fst\ P'' \rangle$  by metis
    next
    case 2
      from this obtain  $A''$  where  $A \gg A''\ B = A''$  by metis
      thus ?thesis using fst2 by metis
    next
  qed
next
case (snd1 P P')
  from this obtain  $P''$  where  $P \gg P''\ B = Snd\ P''$ 
    using parallel-reduction-sndE by blast
  thus ?case using snd1.IH parallel-reduction.snd1 by metis
next
case (snd2 C A' A B)
  from this consider
     $\exists P''. ((Pair\ A\ C) \gg P'') \wedge B = Snd\ P''$ 
  |  $\exists C''. (C \gg C'') \wedge (B = C'')$ 
  using parallel-reduction-sndE[where  $P=(Pair\ A\ C)$  and  $X=B$ ] using
  trm-simp(5, 6) by metis
  thus ?case proof(cases)
    case 1
      from this obtain  $P''$  where  $(Pair\ A\ C) \gg P''$  and  $B = Snd\ P''$  by auto
      from this obtain  $A''\ C''$  where  $P'' = Pair\ A''\ C''$   $A \gg A''\ C \gg C''$ 
        using parallel-reduction-pairE by metis
      thus ?thesis using snd2 parallel-reduction.snd2  $\langle B = Snd\ P'' \rangle$  by metis
    next
    case 2
      from this obtain  $C''$  where  $C \gg C''\ B = C''$  by metis
      thus ?thesis using snd2 by metis
    next
  qed
next
qed

```

lemma parallel-reduction-diamond:

assumes $A \gg B \ A \gg C$
shows $\exists D. (B \gg D) \wedge (C \gg D)$
proof –
obtain D **where** $A \gg \gg D$ **using** *complete-development-exists* **by** *metis*
hence $(B \gg D) \wedge (C \gg D)$ **using** *complete-development-triangle* *assms* **by**
auto
thus *?thesis* **by** *blast*
qed

inductive *parallel-reduces* :: '*a trm* \Rightarrow '*a trm* \Rightarrow *bool* ($- \gg^* -$) **where**
reflexive: $A \gg^* A$
| *transitive*: $[A \gg^* A'; A' \gg A''] \Longrightarrow A \gg^* A''$

lemma *parallel-reduces-diamond'*:
assumes $A \gg^* C \ A \gg B$
shows $\exists D. (B \gg^* D) \wedge (C \gg D)$
using *assms* **proof**(*induction*)
case (*reflexive* A)
thus *?case* **using** *parallel-reduces.reflexive* **by** *metis*
next
case (*transitive* $A \ A' \ A''$)
from *this* **obtain** C **where** $B \gg^* C \ A' \gg C$ **by** *metis*
from $\langle A' \gg C \rangle \langle A' \gg A'' \rangle$ **obtain** D **where** $C \gg D \ A'' \gg D$
using *parallel-reduction-diamond* **by** *metis*
thus *?case* **using** *parallel-reduces.transitive* $\langle B \gg^* C \rangle$ **by** *metis*
next
qed

lemma *parallel-reduces-diamond*:
assumes $A \gg^* B \ A \gg^* C$
shows $\exists D. (B \gg^* D) \wedge (C \gg^* D)$
using *assms* **proof**(*induction*)
case (*reflexive* A)
thus *?case* **using** *parallel-reduces.reflexive* **by** *metis*
next
case (*transitive* $A \ A' \ A''$)
from *this* **obtain** C' **where** $A' \gg^* C' \ C \gg^* C'$ **by** *metis*
from *this* **obtain** D **where** $A'' \gg^* D \ C' \gg D$
using $\langle A' \gg A'' \rangle \langle A' \gg^* C' \rangle$ *parallel-reduces-diamond'* **by** *metis*
thus *?case* **using** *parallel-reduces.transitive* $\langle C \gg^* C' \rangle$ **by** *metis*
next
qed

lemma *beta-reduction-is-parallel-reduction*:
assumes $A \rightarrow \beta B$
shows $A \gg B$
using *assms*
apply *induction*
apply (*metis* *parallel-reduction.beta* *parallel-reduction.refl*)

```

apply (metis parallel-reduction.app parallel-reduction.refl)
apply (metis parallel-reduction.app parallel-reduction.refl)
apply (metis parallel-reduction.eta)
apply (metis parallel-reduction.pair parallel-reduction.refl)
apply (metis parallel-reduction.pair parallel-reduction.refl)
apply (metis parallel-reduction.fst1)
apply (metis parallel-reduction.fst2 parallel-reduction.refl)
apply (metis parallel-reduction.snd1)
apply (metis parallel-reduction.snd2 parallel-reduction.refl)
done

```

lemma *parallel-reduction-is-beta-reduction*:

```

assumes  $A >> B$ 
shows  $A \rightarrow\beta^* B$ 
using assms proof(induction)
  case (refl  $A$ )
    thus ?case using beta-reduces.reflexive.
  next
  case (beta  $A A' B B' x T$ )
    hence  $(App (Fn x T A) B) \rightarrow\beta^* (App (Fn x T A') B')$ 
      using  $\langle A \rightarrow\beta^* A' \rangle$ 
      beta-reduces-fn beta-reduces-app-left beta-reduces-app-right beta-reduces-composition
      by metis
    moreover have  $(App (Fn x T A') B') \rightarrow\beta (A'[x ::= B'])$ 
      using beta-reduction.beta.
    ultimately show ?case using beta-reduces.transitive by metis
  next
  case (eta  $A A' x T$ )
    thus ?case using beta-reduces-fn by metis
  next
  case (app  $A A' B B'$ )
    thus ?case using beta-reduces-app-left beta-reduces-app-right beta-reduces-composition
by metis
  next
  case (pair  $A A' B B'$ )
    thus ?case using beta-reduces-pair-left beta-reduces-pair-right beta-reduces-composition
by metis
  next
  case (fst1  $P P'$ )
    thus ?case using beta-reduces-fst by metis
  next
  case (fst2  $A A' B$ )
    thus ?case
      using beta-reduces-pair-left beta-reduction.fst2 beta-reduces.intros beta-reduces-composition
      by blast
  next
  case (snd1  $P P'$ )
    thus ?case using beta-reduces-snd by metis
  next

```

```

case (snd2 B B' A)
  thus ?case
  using beta-reduces-pair-left beta-reduction.snd2 beta-reduces.intros beta-reduces-composition
  by blast
next
qed

```

```

lemma parallel-beta-reduces-equivalent:
  shows  $(A \gg^* B) = (A \rightarrow\beta^* B)$ 
proof -
  have  $\rightarrow: (A \gg^* B) \implies (A \rightarrow\beta^* B)$ 
  proof(induction rule: parallel-reduces.induct)
    case (reflexive A)
      thus ?case using beta-reduces.reflexive.
    next
    case (transitive A A' A'')
      thus ?case using beta-reduces-composition parallel-reduction-is-beta-reduction
  by metis
  next
  qed

```

```

have  $\leftarrow: (A \rightarrow\beta^* B) \implies (A \gg^* B)$ 
proof(induction rule: beta-reduces.induct)
  case (reflexive A)
    thus ?case using parallel-reduces.reflexive.
  next
  case (transitive A A' A'')
    thus ?case using parallel-reduces.transitive beta-reduction-is-parallel-reduction
by metis
next
qed

```

```

from  $\leftarrow \rightarrow$  show  $(A \gg^* B) = (A \rightarrow\beta^* B)$  by blast
qed

```

```

theorem confluence:
  assumes  $A \rightarrow\beta^* B$   $A \rightarrow\beta^* C$ 
  shows  $\exists D. (B \rightarrow\beta^* D) \wedge (C \rightarrow\beta^* D)$ 
proof -
  from assms have  $A \gg^* B$   $A \gg^* C$  using parallel-beta-reduces-equivalent by
metis+
  hence  $\exists D. (B \gg^* D) \wedge (C \gg^* D)$  using parallel-reduces-diamond by metis
  thus  $\exists D. (B \rightarrow\beta^* D) \wedge (C \rightarrow\beta^* D)$  using parallel-beta-reduces-equivalent by
metis
qed

```

```

end
end

```