

Embedding of the Theory of Abstract Objects in Isabelle/HOL

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Abstract

This document constitutes a core contribution of the MSc project of Daniel Kirchner. The supervisor of this project is Christoph Benzmüller. The project idea results from an ongoing collaboration between Benzmüller and Zalta since 2015 and from the Computational Metaphysics lecture course held at FU Berlin in 2016.

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1 Embedding

1.1 Primitives

typedec1 i — possible worlds
typedec1 j — states
typedef $o = UNIV :: (j \Rightarrow i \Rightarrow bool)$ *set*
morphisms *evalo makeo ..* — truth values

consts $dw :: i$ — actual world
consts $dj :: j$ — actual state

typedec1 ω — ordinary objects
typedec1 σ — special Urelements
datatype $v = \omega v \ \omega \mid \sigma v \ \sigma$ — Urelements

type-synonym $\Pi_0 = o$ — zero place relations
typedef $\Pi_1 = UNIV :: (v \Rightarrow j \Rightarrow i \Rightarrow bool)$ *set*
morphisms *evalPi1 makePi1 ..* — one place relations
typedef $\Pi_2 = UNIV :: (v \Rightarrow v \Rightarrow j \Rightarrow i \Rightarrow bool)$ *set*
morphisms *evalPi2 makePi2 ..* — two place relations
typedef $\Pi_3 = UNIV :: (v \Rightarrow v \Rightarrow v \Rightarrow j \Rightarrow i \Rightarrow bool)$ *set*
morphisms *evalPi3 makePi3 ..* — three place relations

type-synonym $\alpha = \Pi_1$ *set* — abstract objects

datatype $\nu = \omega \nu \ \omega \mid \alpha \nu \ \alpha$ — individuals

Remark 1. *Individual terms can be definite descriptions which may not denote. The condition under which an individual term denotes is stored as a boolean. Note that relation terms on the other hand always denote, so there is no need for a distinction between relation terms and relation variables.*

typedef $\kappa = UNIV :: (bool \times \nu)$ *set* **morphisms** *evalk makek ..*

setup-lifting *type-definition-o*
setup-lifting *type-definition- κ*
setup-lifting *type-definition- Π_1*
setup-lifting *type-definition- Π_2*
setup-lifting *type-definition- Π_3*

Remark 2. *Individual terms can be explicitly marked to represent only denoting resp. logically proper objects.*

lift-definition $\nu \kappa :: \nu \Rightarrow \kappa \ (-^P \ [90] \ 90)$ *is Pair True* .
lift-definition *denotes* $:: \kappa \Rightarrow bool$ *is fst* .
lift-definition *denotation* $:: \kappa \Rightarrow \nu$ *is snd* .

1.2 Mapping from abstract objects to special Urelements

consts $\alpha \sigma :: \alpha \Rightarrow \sigma$
axiomatization where $\alpha \sigma$ -*surj*: *surj* $\alpha \sigma$

1.3 Conversion between objects and Urelements

definition $\nu\nu :: \nu \Rightarrow v$ **where** $\nu\nu \equiv \text{case-}\nu \ \omega\nu \ (\sigma\nu \circ \alpha\sigma)$

definition $v\nu :: v \Rightarrow \nu$ **where** $v\nu \equiv \text{case-}v \ \omega\nu \ (\alpha\nu \circ (\text{inv } \alpha\sigma))$

1.4 Exemplification of n-place relations.

Remark 3. An exemplification formula is only true if all individual variables denote. Furthermore exemplification only depends on the Urelement corresponding to the individual.

lift-definition $\text{exe0} :: \Pi_0 \Rightarrow o \ (\llbracket - \rrbracket)$ **is** id .

lift-definition $\text{exe1} :: \Pi_1 \Rightarrow \kappa \Rightarrow o \ (\llbracket -, - \rrbracket)$ **is**

$\lambda F \ x \ w \ s . (\text{denotes } x) \wedge F (\nu\nu (\text{denotation } x)) \ w \ s .$

lift-definition $\text{exe2} :: \Pi_2 \Rightarrow \kappa \Rightarrow \kappa \Rightarrow o \ (\llbracket -, -, - \rrbracket)$ **is**

$\lambda F \ x \ y \ w \ s . (\text{denotes } x) \wedge (\text{denotes } y) \wedge$
 $F (\nu\nu (\text{denotation } x)) (\nu\nu (\text{denotation } y)) \ w \ s .$

lift-definition $\text{exe3} :: \Pi_3 \Rightarrow \kappa \Rightarrow \kappa \Rightarrow \kappa \Rightarrow o \ (\llbracket -, -, -, - \rrbracket)$ **is**

$\lambda F \ x \ y \ z \ w \ s . (\text{denotes } x) \wedge (\text{denotes } y) \wedge (\text{denotes } z) \wedge$
 $F (\nu\nu (\text{denotation } x)) (\nu\nu (\text{denotation } y)) (\nu\nu (\text{denotation } z)) \ w \ s .$

1.5 Encoding

Remark 4. An encoding formula is again only true if the individual term denotes. Furthermore ordinary objects never encode, whereas abstract objects encode a property if and only if the property is contained in it as per the Aczel Model.

lift-definition $\text{enc} :: \kappa \Rightarrow \Pi_1 \Rightarrow o \ (\llbracket -, - \rrbracket)$ **is**

$\lambda x \ F \ w \ s . (\text{denotes } x) \wedge \text{case-}\nu \ (\lambda \omega . F \omega . \text{False}) (\lambda \alpha . F \in \alpha) (\text{denotation } x) .$

1.6 Connectives and Quantifiers

Remark 5. The connectives behave classically if evaluated for the actual state dj , whereas their behavior is governed by uninterpreted constants for any other state.

consts $I\text{-NOT} :: j \Rightarrow (i \Rightarrow \text{bool}) \Rightarrow (i \Rightarrow \text{bool})$

consts $I\text{-IMPL} :: j \Rightarrow (i \Rightarrow \text{bool}) \Rightarrow (i \Rightarrow \text{bool}) \Rightarrow (i \Rightarrow \text{bool})$

lift-definition $\text{not} :: o \Rightarrow o \ (\neg - \text{ [54] } 70)$ **is**

$\lambda p \ s \ w . s = dj \wedge \neg p \ dj \ w \vee s \neq dj \wedge (I\text{-NOT } s \ (p \ s) \ w) .$

lift-definition $\text{impl} :: o \Rightarrow o \Rightarrow o \ (\text{infixl } \rightarrow \text{ [51] } 51)$ **is**

$\lambda p \ q \ s \ w . s = dj \wedge (p \ dj \ w \longrightarrow q \ dj \ w) \vee s \neq dj \wedge (I\text{-IMPL } s \ (p \ s) \ (q \ s)) \ w .$

lift-definition $\text{forall}_\nu :: (\nu \Rightarrow o) \Rightarrow o \ (\text{binder } \forall_\nu \text{ [8] } 9)$ **is**

$\lambda \varphi \ s \ w . \forall x :: \nu . (\varphi \ x) \ s \ w .$

lift-definition $\text{forall}_0 :: (\Pi_0 \Rightarrow o) \Rightarrow o \ (\text{binder } \forall_0 \text{ [8] } 9)$ **is**

$\lambda \varphi \ s \ w . \forall x :: \Pi_0 . (\varphi \ x) \ s \ w .$

lift-definition $\text{forall}_1 :: (\Pi_1 \Rightarrow o) \Rightarrow o \ (\text{binder } \forall_1 \text{ [8] } 9)$ **is**

$\lambda \varphi \ s \ w . \forall x :: \Pi_1 . (\varphi \ x) \ s \ w .$

lift-definition $\text{forall}_2 :: (\Pi_2 \Rightarrow o) \Rightarrow o \ (\text{binder } \forall_2 \text{ [8] } 9)$ **is**

$\lambda \varphi \ s \ w . \forall x :: \Pi_2 . (\varphi \ x) \ s \ w .$

lift-definition $\text{forall}_3 :: (\Pi_3 \Rightarrow o) \Rightarrow o \ (\text{binder } \forall_3 \text{ [8] } 9)$ **is**

$\lambda \varphi \ s \ w . \forall x :: \Pi_3 . (\varphi \ x) \ s \ w .$

lift-definition $\text{forall}_o :: (o \Rightarrow o) \Rightarrow o \ (\text{binder } \forall_o \text{ [8] } 9)$ **is**

$\lambda \varphi \ s \ w . \forall x :: o . (\varphi \ x) \ s \ w .$

lift-definition $\text{box} :: o \Rightarrow o \ (\Box - \text{ [62] } 63)$ **is**

$\lambda p \ s \ w . \forall v . p \ s \ v .$

lift-definition $\text{actual} :: o \Rightarrow o \ (\mathcal{A} - \text{ [64] } 65)$ **is**

$\lambda p \ s \ w . p \ dj \ dw .$

1.7 Definite Description

Remark 6. Definite descriptions map conditions on individual variables to individual terms. Whether the condition is satisfied by a unique individual (and therefore the definite description denotes) is stored as a boolean.

lift-definition *that::*($\nu \Rightarrow o$) $\Rightarrow \kappa$ (**binder** ι [8] 9) is
 $\lambda \varphi . (\exists ! x . (\varphi x) \text{ dj } dw, \text{ THE } x . (\varphi x) \text{ dj } dw) .$

1.8 Lambda Expressions

Remark 7. *Lambda expressions map functions acting on individual variables to functions acting on Urelements (i.e. relations). Note that the inverse mapping $\nu\nu$ is injective only for ordinary objects. As propositional formulas, which are the only terms PM allows inside lambda expressions, do not contain encoding subformulas, they only depends on Urelements, though. For propositional formulas the lambda expressions therefore exactly correspond to the lambda expressions in PM. Lambda expressions with non-propositional formulas, which are not allowed in PM, because in general they lead to inconsistencies, have a non-standard semantics. $\lambda x . \{x^P, F\}$ can be translated to "being x such that there exists an abstract object, which encodes F , that is mapped to the same Urelement as x " instead of "being x such that x encodes F ". This construction avoids the aforementioned inconsistencies.*

lift-definition *lambdabinder0* :: $o \Rightarrow \Pi_0 (\lambda^0)$ is *id* .

lift-definition *lambdabinder1* :: $(\nu \Rightarrow o) \Rightarrow \Pi_1 (\text{binder } \lambda [8] 9)$ is
 $\lambda \varphi u . \varphi (\nu u) .$

lift-definition *lambdabinder2* :: $(\nu \Rightarrow \nu \Rightarrow o) \Rightarrow \Pi_2 (\lambda^2)$ is
 $\lambda \varphi u v . \varphi (\nu u) (\nu v) .$

lift-definition *lambdabinder3* :: $(\nu \Rightarrow \nu \Rightarrow \nu \Rightarrow o) \Rightarrow \Pi_3 (\lambda^3)$ is
 $\lambda \varphi u v w . \varphi (\nu u) (\nu v) (\nu w) .$

1.9 Validity

Remark 8. *A formula is considered semantically valid for a possible world, if it evaluates to True for the actual state and the given possible world.*

lift-definition *valid-in* :: $i \Rightarrow o \Rightarrow \text{bool}$ (**infixl** \models 5) is
 $\lambda v \varphi . \varphi \text{ dj } v .$

1.10 Concreteness

Remark 9. *In order to define concreteness, care has to be taken that the defined notion of concreteness coincides with the meta-logical distinction between abstract objects and ordinary objects. Furthermore the axioms about concreteness have to be satisfied. This is achieved by introducing an uninterpreted that determines whether an ordinary object is concrete in a given possible world. This constant is axiomatized, such that all ordinary objects are possibly concrete, contingent objects possibly exist and possibly no contingent objects exist.*

consts *ConcreteInWorld* :: $\omega \Rightarrow i \Rightarrow \text{bool}$

abbreviation *OrdinaryObjectsPossiblyConcrete* **where**

OrdinaryObjectsPossiblyConcrete $\equiv \forall x . \exists v . \text{ConcreteInWorld } x v$

abbreviation *PossiblyContingentObjectExists* **where**

PossiblyContingentObjectExists $\equiv \exists x v . \text{ConcreteInWorld } x v$
 $\wedge (\exists w . \neg \text{ConcreteInWorld } x w)$

abbreviation *PossiblyNoContingentObjectExists* **where**

PossiblyNoContingentObjectExists $\equiv \exists w . \forall x . \text{ConcreteInWorld } x w$
 $\longrightarrow (\forall v . \text{ConcreteInWorld } x v)$

axiomatization **where**

OrdinaryObjectsPossiblyConcreteAxiom:

OrdinaryObjectsPossiblyConcrete

and *PossiblyContingentObjectExistsAxiom:*

PossiblyContingentObjectExists

and *PossiblyNoContingentObjectExistsAxiom:*

PossiblyNoContingentObjectExists

Remark 10. *Concreteness of ordinary objects can now be defined using this axiomatized uninterpreted constant. Abstract objects on the other hand are never concrete.*

lift-definition *Concrete*:: $\Pi_1 (E!)$ is

$\lambda u s w . \text{case } u \text{ of } \omega v x \Rightarrow \text{ConcreteInWorld } x w \mid - \Rightarrow \text{False} .$

1.11 Automation

named-theorems meta-defs

```
declare not-def[meta-defs] impl-def[meta-defs] forallν-def[meta-defs]
  forall0-def[meta-defs] forall1-def[meta-defs]
  forall2-def[meta-defs] forall3-def[meta-defs] forallo-def[meta-defs]
  box-def[meta-defs] actual-def[meta-defs] that-def[meta-defs]
  lambdabinder0-def[meta-defs] lambdabinder1-def[meta-defs]
  lambdabinder2-def[meta-defs] lambdabinder3-def[meta-defs]
  exe0-def[meta-defs] exe1-def[meta-defs] exe2-def[meta-defs]
  exe3-def[meta-defs] enc-def[meta-defs] inv-def[meta-defs]
  that-def[meta-defs] valid-in-def[meta-defs] Concrete-def[meta-defs]
```

```
declare [[smt-solver = cvc4]]
```

```
declare [[simp-depth-limit = 10]]
```

```
declare [[unify-search-bound = 40]]
```

1.12 Auxiliary Lemmata

named-theorems meta-aux

```
declare makeκ-inverse[meta-aux] evalκ-inverse[meta-aux]
  makeo-inverse[meta-aux] evalo-inverse[meta-aux]
  makeΠ1-inverse[meta-aux] evalΠ1-inverse[meta-aux]
  makeΠ2-inverse[meta-aux] evalΠ2-inverse[meta-aux]
  makeΠ3-inverse[meta-aux] evalΠ3-inverse[meta-aux]
lemma νν-ων-is-ων[meta-aux]: νν (ων x) = ων x by (simp add: νν-def)
lemma νν-ων-is-ων[meta-aux]: νν (ων x) = ων x by (simp add: νν-def)
lemma denotation-proper[meta-aux]: denotation (xP) = x
  by (simp add: meta-aux νκ-def denotation-def)
lemma proper-denotes[meta-aux]: denotes (xP)
  by (simp add: meta-aux νκ-def denotes-def)
lemma proper-denotation[meta-aux]: denotation (xP) = x
  by (simp add: meta-aux νκ-def denotation-def)
lemma νν-νν-id[meta-aux]: νν (νν (x)) = x
  by (simp add: νν-def νν-def ασ-surj surj-f-inv-f split: v.split)
lemma no-αω[meta-aux]: ¬(νν (αν x) = ων y) by (simp add: νν-def)
lemma no-σω[meta-aux]: ¬(σν x = ων y) by blast
lemma νν-surj[meta-aux]: surj νν using νν-νν-id surjI by blast
lemma νκ-aux1[meta-aux]:
  fst (evalκ (νν (νν (snd (evalκ x))))P)
  apply transfer
  by simp
lemma νκ-aux2[meta-aux]:
  (νν (snd (evalκ (νν (νν (snd (evalκ x))))P))) = (νν (snd (evalκ x)))
  apply transfer
  using νν-νν-id by auto
```

2 Basic Definitions

2.1 Derived Connectives

definition diamond::o⇒o (◇- [62] 63) **where**

diamond ≡ λ φ . ¬□¬φ

definition conj::o⇒o⇒o (infixl & 53) **where**

conj ≡ λ x y . ¬(x → ¬y)

definition disj::o⇒o⇒o (infixl ∨ 52) **where**

disj ≡ λ x y . ¬x → y

definition equiv::o⇒o⇒o (infixl ≡ 51) **where**

equiv ≡ λ x y . (x → y) & (y → x)

named-theorems *conn-defs*
declare *diamond-def*[*conn-defs*] *conj-def*[*conn-defs*]
disj-def[*conn-defs*] *equiv-def*[*conn-defs*]

2.2 Abstract and Ordinary Objects

definition *Ordinary* :: $\Pi_1 (O!)$ **where** *Ordinary* $\equiv \lambda x. \Diamond \langle E!, x^P \rangle$
definition *Abstract* :: $\Pi_1 (A!)$ **where** *Abstract* $\equiv \lambda x. \neg \Diamond \langle E!, x^P \rangle$

2.3 Identity Definitions

definition *basic-identity_E* :: Π_2 **where**
basic-identity_E $\equiv \lambda^2 (\lambda x y. \langle O!, x^P \rangle \ \& \ \langle O!, y^P \rangle$
 $\ \& \ \Box (\forall_1 F. \langle F, x^P \rangle \equiv \langle F, y^P \rangle))$

definition *basic-identity_E-infix* :: $\kappa \Rightarrow \kappa \Rightarrow o$ (**infixl** =_E 63) **where**
 $x =_E y \equiv \langle \text{basic-identity}_E, x, y \rangle$

definition *basic-identity _{κ}* (**infixl** = _{κ} 63) **where**
basic-identity _{κ} $\equiv \lambda x y. (x =_E y) \vee \langle A!, x \rangle \ \& \ \langle A!, y \rangle$
 $\ \& \ \Box (\forall_1 F. \langle x, F \rangle \equiv \langle y, F \rangle)$

definition *basic-identity₁* (**infixl** =₁ 63) **where**
basic-identity₁ $\equiv \lambda F G. \Box (\forall_\nu x. \langle x^P, F \rangle \equiv \langle x^P, G \rangle)$

definition *basic-identity₂* :: $\Pi_2 \Rightarrow \Pi_2 \Rightarrow o$ (**infixl** =₂ 63) **where**
basic-identity₂ $\equiv \lambda F G. \forall_\nu x y. ((\lambda y. \langle F, x^P, y^P \rangle) =_1 (\lambda y. \langle G, x^P, y^P \rangle))$
 $\ \& \ ((\lambda y. \langle F, y^P, x^P \rangle) =_1 (\lambda y. \langle G, y^P, x^P \rangle))$

definition *basic-identity₃* :: $\Pi_3 \Rightarrow \Pi_3 \Rightarrow o$ (**infixl** =₃ 63) **where**
basic-identity₃ $\equiv \lambda F G. \forall_\nu x y. (\lambda z. \langle F, z^P, x^P, y^P \rangle) =_1 (\lambda z. \langle G, z^P, x^P, y^P \rangle)$
 $\ \& \ (\lambda z. \langle F, x^P, z^P, y^P \rangle) =_1 (\lambda z. \langle G, x^P, z^P, y^P \rangle)$
 $\ \& \ (\lambda z. \langle F, x^P, y^P, z^P \rangle) =_1 (\lambda z. \langle G, x^P, y^P, z^P \rangle)$

definition *basic-identity_o* :: $o \Rightarrow o \Rightarrow o$ (**infixl** =_o 63) **where**
basic-identity_o $\equiv \lambda F G. (\lambda y. F) =_1 (\lambda y. G)$

3 Semantics

3.1 Propositional Formulas

Remark 11. *The embedding extends the notion of propositional formulas to functions that are propositional in the individual variables that are their parameters, i.e. their parameters only occur in exemplification and not in encoding subformulas. This weaker condition is enough to prove the semantics of propositional formulas.*

named-theorems *IsPropositional-intros*

definition *IsPropositionalInX* :: $(\kappa \Rightarrow o) \Rightarrow \text{bool}$ **where**
IsPropositionalInX $\equiv \lambda \Theta. \exists \chi. \Theta = (\lambda x. \chi$
 $\ (\text{* one place *}) (\lambda F. \langle F, x \rangle)$
 $\ (\text{* two place *}) (\lambda F. \langle F, x, x \rangle) (\lambda F a. \langle F, x, a \rangle) (\lambda F a. \langle F, a, x \rangle)$
 $\ (\text{* three place three x *}) (\lambda F. \langle F, x, x, x \rangle)$
 $\ (\text{* three place two x *}) (\lambda F a. \langle F, x, x, a \rangle) (\lambda F a. \langle F, x, a, x \rangle)$
 $\ (\lambda F a. \langle F, a, x, x \rangle)$
 $\ (\text{* three place one x *}) (\lambda F a b. \langle F, x, a, b \rangle) (\lambda F a b. \langle F, a, x, b \rangle)$
 $\ (\lambda F a b. \langle F, a, b, x \rangle))$

lemma *IsPropositionalInX-intro*[*IsPropositional-intros*]:

IsPropositionalInX $(\lambda x. \chi$
 $\ (\text{* one place *}) (\lambda F. \langle F, x \rangle)$
 $\ (\text{* two place *}) (\lambda F. \langle F, x, x \rangle) (\lambda F a. \langle F, x, a \rangle) (\lambda F a. \langle F, a, x \rangle)$

(* three place three x *) ($\lambda F . \langle F, x, x, x \rangle$)
 (* three place two x *) ($\lambda F a . \langle F, x, x, a \rangle$) ($\lambda F a . \langle F, x, a, x \rangle$)
 ($\lambda F a . \langle F, a, x, x \rangle$)
 (* three place one x *) ($\lambda F a b . \langle F, x, a, b \rangle$) ($\lambda F a b . \langle F, a, x, b \rangle$)
 ($\lambda F a b . \langle F, a, b, x \rangle$)

unfolding *IsPropositionalInX-def* **by** *blast*

definition *IsPropositionalInXY* :: $(\kappa \Rightarrow \kappa \Rightarrow o) \Rightarrow \text{bool}$ **where**

IsPropositionalInXY $\equiv \lambda \Theta . \exists \chi . \Theta = (\lambda x y . \chi$

(* only x *)
 (* one place *) ($\lambda F . \langle F, x \rangle$)
 (* two place *) ($\lambda F . \langle F, x, x \rangle$) ($\lambda F a . \langle F, x, a \rangle$) ($\lambda F a . \langle F, a, x \rangle$)
 (* three place three x *) ($\lambda F . \langle F, x, x, x \rangle$)
 (* three place two x *) ($\lambda F a . \langle F, x, x, a \rangle$) ($\lambda F a . \langle F, x, a, x \rangle$)
 ($\lambda F a . \langle F, a, x, x \rangle$)
 (* three place one x *) ($\lambda F a b . \langle F, x, a, b \rangle$) ($\lambda F a b . \langle F, a, x, b \rangle$)
 ($\lambda F a b . \langle F, a, b, x \rangle$)
 (* only y *)
 (* one place *) ($\lambda F . \langle F, y \rangle$)
 (* two place *) ($\lambda F . \langle F, y, y \rangle$) ($\lambda F a . \langle F, y, a \rangle$) ($\lambda F a . \langle F, a, y \rangle$)
 (* three place three y *) ($\lambda F . \langle F, y, y, y \rangle$)
 (* three place two y *) ($\lambda F a . \langle F, y, y, a \rangle$) ($\lambda F a . \langle F, y, a, y \rangle$)
 ($\lambda F a . \langle F, a, y, y \rangle$)
 (* three place one y *) ($\lambda F a b . \langle F, y, a, b \rangle$) ($\lambda F a b . \langle F, a, y, b \rangle$)
 ($\lambda F a b . \langle F, a, b, y \rangle$)
 (* x and y *)
 (* two place *) ($\lambda F . \langle F, x, y \rangle$) ($\lambda F . \langle F, y, x \rangle$)
 (* three place (x,y) *) ($\lambda F a . \langle F, x, y, a \rangle$) ($\lambda F a . \langle F, x, a, y \rangle$)
 ($\lambda F a . \langle F, a, x, y \rangle$)
 (* three place (y,x) *) ($\lambda F a . \langle F, y, x, a \rangle$) ($\lambda F a . \langle F, y, a, x \rangle$)
 ($\lambda F a . \langle F, a, y, x \rangle$)
 (* three place (x,x,y) *) ($\lambda F . \langle F, x, x, y \rangle$) ($\lambda F . \langle F, x, y, x \rangle$) ($\lambda F . \langle F, y, x, x \rangle$)
 (* three place (x,y,y) *) ($\lambda F . \langle F, x, y, y \rangle$) ($\lambda F . \langle F, y, x, y \rangle$) ($\lambda F . \langle F, y, y, x \rangle$)
 (* three place (x,x,x) *) ($\lambda F . \langle F, x, x, x \rangle$)
 (* three place (y,y,y) *) ($\lambda F . \langle F, y, y, y \rangle$)

lemma *IsPropositionalInXY-intro*[*IsPropositional-intros*]:

IsPropositionalInXY ($\lambda x y . \chi$

(* only x *)
 (* one place *) ($\lambda F . \langle F, x \rangle$)
 (* two place *) ($\lambda F . \langle F, x, x \rangle$) ($\lambda F a . \langle F, x, a \rangle$) ($\lambda F a . \langle F, a, x \rangle$)
 (* three place three x *) ($\lambda F . \langle F, x, x, x \rangle$)
 (* three place two x *) ($\lambda F a . \langle F, x, x, a \rangle$) ($\lambda F a . \langle F, x, a, x \rangle$)
 ($\lambda F a . \langle F, a, x, x \rangle$)
 (* three place one x *) ($\lambda F a b . \langle F, x, a, b \rangle$) ($\lambda F a b . \langle F, a, x, b \rangle$)
 ($\lambda F a b . \langle F, a, b, x \rangle$)
 (* only y *)
 (* one place *) ($\lambda F . \langle F, y \rangle$)
 (* two place *) ($\lambda F . \langle F, y, y \rangle$) ($\lambda F a . \langle F, y, a \rangle$) ($\lambda F a . \langle F, a, y \rangle$)
 (* three place three y *) ($\lambda F . \langle F, y, y, y \rangle$)
 (* three place two y *) ($\lambda F a . \langle F, y, y, a \rangle$) ($\lambda F a . \langle F, y, a, y \rangle$)
 ($\lambda F a . \langle F, a, y, y \rangle$)
 (* three place one y *) ($\lambda F a b . \langle F, y, a, b \rangle$) ($\lambda F a b . \langle F, a, y, b \rangle$)
 ($\lambda F a b . \langle F, a, b, y \rangle$)
 (* x and y *)
 (* two place *) ($\lambda F . \langle F, x, y \rangle$) ($\lambda F . \langle F, y, x \rangle$)
 (* three place (x,y) *) ($\lambda F a . \langle F, x, y, a \rangle$) ($\lambda F a . \langle F, x, a, y \rangle$)
 ($\lambda F a . \langle F, a, x, y \rangle$)
 (* three place (y,x) *) ($\lambda F a . \langle F, y, x, a \rangle$) ($\lambda F a . \langle F, y, a, x \rangle$)
 ($\lambda F a . \langle F, a, y, x \rangle$)
 (* three place (x,x,y) *) ($\lambda F . \langle F, x, x, y \rangle$) ($\lambda F . \langle F, x, y, x \rangle$)
 ($\lambda F . \langle F, y, x, x \rangle$)
 (* three place (x,y,y) *) ($\lambda F . \langle F, x, y, y \rangle$) ($\lambda F . \langle F, y, x, y \rangle$)

$(\lambda F . \langle F, y, y, x \rangle)$
 $(* \text{ three place } (x, x, x) *) (\lambda F . \langle F, x, x, x \rangle)$
 $(* \text{ three place } (y, y, y) *) (\lambda F . \langle F, y, y, y \rangle)$
unfolding *IsPropositionalInXYZ-def by metis*

definition *IsPropositionalInXYZ* :: $(\kappa \Rightarrow \kappa \Rightarrow \kappa \Rightarrow o) \Rightarrow \text{bool}$ **where**

$\text{IsPropositionalInXYZ} \equiv \lambda \Theta . \exists \chi . \Theta = (\lambda x y z . \chi$
 $(* \text{ only } x *)$
 $(* \text{ one place } *) (\lambda F . \langle F, x \rangle)$
 $(* \text{ two place } *) (\lambda F . \langle F, x, x \rangle) (\lambda F a . \langle F, x, a \rangle) (\lambda F a . \langle F, a, x \rangle)$
 $(* \text{ three place three } x *) (\lambda F . \langle F, x, x, x \rangle)$
 $(* \text{ three place two } x *) (\lambda F a . \langle F, x, x, a \rangle) (\lambda F a . \langle F, x, a, x \rangle)$
 $(\lambda F a . \langle F, a, x, x \rangle)$
 $(* \text{ three place one } x *) (\lambda F a b . \langle F, x, a, b \rangle) (\lambda F a b . \langle F, a, x, b \rangle)$
 $(\lambda F a b . \langle F, a, b, x \rangle)$
 $(* \text{ only } y *)$
 $(* \text{ one place } *) (\lambda F . \langle F, y \rangle)$
 $(* \text{ two place } *) (\lambda F . \langle F, y, y \rangle) (\lambda F a . \langle F, y, a \rangle) (\lambda F a . \langle F, a, y \rangle)$
 $(* \text{ three place three } y *) (\lambda F . \langle F, y, y, y \rangle)$
 $(* \text{ three place two } y *) (\lambda F a . \langle F, y, y, a \rangle) (\lambda F a . \langle F, y, a, y \rangle)$
 $(\lambda F a . \langle F, a, y, y \rangle)$
 $(* \text{ three place one } y *) (\lambda F a b . \langle F, y, a, b \rangle) (\lambda F a b . \langle F, a, y, b \rangle)$
 $(\lambda F a b . \langle F, a, b, y \rangle)$
 $(* \text{ only } z *)$
 $(* \text{ one place } *) (\lambda F . \langle F, z \rangle)$
 $(* \text{ two place } *) (\lambda F . \langle F, z, z \rangle) (\lambda F a . \langle F, z, a \rangle) (\lambda F a . \langle F, a, z \rangle)$
 $(* \text{ three place three } z *) (\lambda F . \langle F, z, z, z \rangle)$
 $(* \text{ three place two } z *) (\lambda F a . \langle F, z, z, a \rangle) (\lambda F a . \langle F, z, a, z \rangle)$
 $(\lambda F a . \langle F, a, z, z \rangle)$
 $(* \text{ three place one } z *) (\lambda F a b . \langle F, z, a, b \rangle) (\lambda F a b . \langle F, a, z, b \rangle)$
 $(\lambda F a b . \langle F, a, b, z \rangle)$
 $(* \text{ } x \text{ and } y *)$
 $(* \text{ two place } *) (\lambda F . \langle F, x, y \rangle) (\lambda F . \langle F, y, x \rangle)$
 $(* \text{ three place } (x, y) *) (\lambda F a . \langle F, x, y, a \rangle) (\lambda F a . \langle F, x, a, y \rangle)$
 $(\lambda F a . \langle F, a, x, y \rangle)$
 $(* \text{ three place } (y, x) *) (\lambda F a . \langle F, y, x, a \rangle) (\lambda F a . \langle F, y, a, x \rangle)$
 $(\lambda F a . \langle F, a, y, x \rangle)$
 $(* \text{ three place } (x, x, y) *) (\lambda F . \langle F, x, x, y \rangle) (\lambda F . \langle F, x, y, x \rangle)$
 $(\lambda F . \langle F, y, x, x \rangle)$
 $(* \text{ three place } (x, y, y) *) (\lambda F . \langle F, x, y, y \rangle) (\lambda F . \langle F, y, x, y \rangle)$
 $(\lambda F . \langle F, y, y, x \rangle)$
 $(* \text{ three place } (x, x, x) *) (\lambda F . \langle F, x, x, x \rangle)$
 $(* \text{ three place } (y, y, y) *) (\lambda F . \langle F, y, y, y \rangle)$
 $(* \text{ } x \text{ and } z *)$
 $(* \text{ two place } *) (\lambda F . \langle F, x, z \rangle) (\lambda F . \langle F, z, x \rangle)$
 $(* \text{ three place } (x, z) *) (\lambda F a . \langle F, x, z, a \rangle) (\lambda F a . \langle F, x, a, z \rangle)$
 $(\lambda F a . \langle F, a, x, z \rangle)$
 $(* \text{ three place } (z, x) *) (\lambda F a . \langle F, z, x, a \rangle) (\lambda F a . \langle F, z, a, x \rangle)$
 $(\lambda F a . \langle F, a, z, x \rangle)$
 $(* \text{ three place } (x, x, z) *) (\lambda F . \langle F, x, x, z \rangle) (\lambda F . \langle F, x, z, x \rangle)$
 $(\lambda F . \langle F, z, x, x \rangle)$
 $(* \text{ three place } (x, z, z) *) (\lambda F . \langle F, x, z, z \rangle) (\lambda F . \langle F, z, x, z \rangle)$
 $(\lambda F . \langle F, z, z, x \rangle)$
 $(* \text{ three place } (x, x, x) *) (\lambda F . \langle F, x, x, x \rangle)$
 $(* \text{ three place } (z, z, z) *) (\lambda F . \langle F, z, z, z \rangle)$
 $(* \text{ } y \text{ and } z *)$
 $(* \text{ two place } *) (\lambda F . \langle F, y, z \rangle) (\lambda F . \langle F, z, y \rangle)$
 $(* \text{ three place } (y, z) *) (\lambda F a . \langle F, y, z, a \rangle) (\lambda F a . \langle F, y, a, z \rangle)$
 $(\lambda F a . \langle F, a, y, z \rangle)$
 $(* \text{ three place } (z, y) *) (\lambda F a . \langle F, z, y, a \rangle) (\lambda F a . \langle F, z, a, y \rangle)$
 $(\lambda F a . \langle F, a, z, y \rangle)$
 $(* \text{ three place } (y, y, z) *) (\lambda F . \langle F, y, y, z \rangle) (\lambda F . \langle F, y, z, y \rangle)$
 $(\lambda F . \langle F, z, y, y \rangle)$

(* three place (y,z,z) *) (λ F . (F,y,z,z)) (λ F . (F,z,y,z))
 (λ F . (F,z,z,y))
 (* three place (y,y,y) *) (λ F . (F,y,y,y))
 (* three place (z,z,z) *) (λ F . (F,z,z,z))
 (* x y z *)
 (* three place (x,...) *) (λ F . (F,x,y,z)) (λ F . (F,x,z,y))
 (* three place (y,...) *) (λ F . (F,y,x,z)) (λ F . (F,y,z,x))
 (* three place (z,...) *) (λ F . (F,z,x,y)) (λ F . (F,z,y,x))

lemma *IsPropositionalInXYZ-intro*[*IsPropositional-intros*]:

IsPropositionalInXYZ (λ x y z . χ

(* only x *)
 (* one place *) (λ F . (F,x))
 (* two place *) (λ F . (F,x,x)) (λ F a . (F,x,a)) (λ F a . (F,a,x))
 (* three place three x *) (λ F . (F,x,x,x))
 (* three place two x *) (λ F a . (F,x,x,a)) (λ F a . (F,x,a,x))
 (λ F a . (F,a,x,x))
 (* three place one x *) (λ F a b . (F,x,a,b)) (λ F a b . (F,a,x,b))
 (λ F a b . (F,a,b,x))
 (* only y *)
 (* one place *) (λ F . (F,y))
 (* two place *) (λ F . (F,y,y)) (λ F a . (F,y,a)) (λ F a . (F,a,y))
 (* three place three y *) (λ F . (F,y,y,y))
 (* three place two y *) (λ F a . (F,y,y,a)) (λ F a . (F,y,a,y))
 (λ F a . (F,a,y,y))
 (* three place one y *) (λ F a b . (F,y,a,b)) (λ F a b . (F,a,y,b))
 (λ F a b . (F,a,b,y))
 (* only z *)
 (* one place *) (λ F . (F,z))
 (* two place *) (λ F . (F,z,z)) (λ F a . (F,z,a)) (λ F a . (F,a,z))
 (* three place three z *) (λ F . (F,z,z,z))
 (* three place two z *) (λ F a . (F,z,z,a)) (λ F a . (F,z,a,z))
 (λ F a . (F,a,z,z))
 (* three place one z *) (λ F a b . (F,z,a,b)) (λ F a b . (F,a,z,b))
 (λ F a b . (F,a,b,z))
 (* x and y *)
 (* two place *) (λ F . (F,x,y)) (λ F . (F,y,x))
 (* three place (x,y) *) (λ F a . (F,x,y,a)) (λ F a . (F,x,a,y))
 (λ F a . (F,a,x,y))
 (* three place (y,x) *) (λ F a . (F,y,x,a)) (λ F a . (F,y,a,x))
 (λ F a . (F,a,y,x))
 (* three place (x,x,y) *) (λ F . (F,x,x,y)) (λ F . (F,x,y,x))
 (λ F . (F,y,x,x))
 (* three place (x,y,y) *) (λ F . (F,x,y,y)) (λ F . (F,y,x,y))
 (λ F . (F,y,y,x))
 (* three place (x,x,x) *) (λ F . (F,x,x,x))
 (* three place (y,y,y) *) (λ F . (F,y,y,y))
 (* x and z *)
 (* two place *) (λ F . (F,x,z)) (λ F . (F,z,x))
 (* three place (x,z) *) (λ F a . (F,x,z,a)) (λ F a . (F,x,a,z))
 (λ F a . (F,a,x,z))
 (* three place (z,x) *) (λ F a . (F,z,x,a)) (λ F a . (F,z,a,x))
 (λ F a . (F,a,z,x))
 (* three place (x,x,z) *) (λ F . (F,x,x,z)) (λ F . (F,x,z,x))
 (λ F . (F,z,x,x))
 (* three place (x,z,z) *) (λ F . (F,x,z,z)) (λ F . (F,z,x,z))
 (λ F . (F,z,z,x))
 (* three place (x,x,x) *) (λ F . (F,x,x,x))
 (* three place (z,z,z) *) (λ F . (F,z,z,z))
 (* y and z *)
 (* two place *) (λ F . (F,y,z)) (λ F . (F,z,y))
 (* three place (y,z) *) (λ F a . (F,y,z,a)) (λ F a . (F,y,a,z))
 (λ F a . (F,a,y,z))

```

named-theorems IsPropositionalIn-defs
declare IsPropositionalInX-def [IsPropositionalIn-defs]
         IsPropositionalInXY-def [IsPropositionalIn-defs]
         IsPropositionalInXYZ-def [IsPropositionalIn-defs]

```

$d_2\text{-def}[semantics\text{-defs}]$ $d_3\text{-def}[semantics\text{-defs}]$
 $ex0\text{-def}[semantics\text{-defs}]$ $ex1\text{-def}[semantics\text{-defs}]$
 $ex2\text{-def}[semantics\text{-defs}]$ $ex3\text{-def}[semantics\text{-defs}]$
 $en\text{-def}[semantics\text{-defs}]$ $d_\kappa\text{-def}[semantics\text{-defs}]$
 $w_0\text{-def}[semantics\text{-defs}]$

Semantics for exemplification and encoding.

lemma $T1\text{-}1[semantics]$:

$(w \models \langle F, x \rangle) = (\exists r \ o_1 . \text{Some } r = d_1 F \wedge \text{Some } o_1 = d_\kappa x \wedge o_1 \in ex1 \ r \ w)$

unfolding $semantics\text{-defs}$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$ $denotation\text{-def}$ $denotes\text{-def}$)

lemma $T1\text{-}2[semantics]$:

$(w \models \langle F, x, y \rangle) = (\exists r \ o_1 \ o_2 . \text{Some } r = d_2 F \wedge \text{Some } o_1 = d_\kappa x$
 $\wedge \text{Some } o_2 = d_\kappa y \wedge (o_1, o_2) \in ex2 \ r \ w)$

unfolding $semantics\text{-defs}$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$ $denotation\text{-def}$ $denotes\text{-def}$)

lemma $T1\text{-}3[semantics]$:

$(w \models \langle F, x, y, z \rangle) = (\exists r \ o_1 \ o_2 \ o_3 . \text{Some } r = d_3 F \wedge \text{Some } o_1 = d_\kappa x$
 $\wedge \text{Some } o_2 = d_\kappa y \wedge \text{Some } o_3 = d_\kappa z$
 $\wedge (o_1, o_2, o_3) \in ex3 \ r \ w)$

unfolding $semantics\text{-defs}$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$ $denotation\text{-def}$ $denotes\text{-def}$)

lemma $T2[semantics]$:

$(w \models \langle x, F \rangle) = (\exists r \ o_1 . \text{Some } r = d_1 F \wedge \text{Some } o_1 = d_\kappa x \wedge o_1 \in en \ r)$

unfolding $semantics\text{-defs}$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$ $denotation\text{-def}$ $denotes\text{-def}$ $split$: $\nu.split$)

lemma $T3[semantics]$:

$(w \models \langle F \rangle) = (\exists r . \text{Some } r = d_0 F \wedge ex0 \ r \ w)$

unfolding $semantics\text{-defs}$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

Semantics for connectives and quantifiers.

lemma $T4[semantics]$: $(w \models \neg\psi) = (\neg(w \models \psi))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T5[semantics]$: $(w \models \psi \rightarrow \chi) = (\neg(w \models \psi) \vee (w \models \chi))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T6[semantics]$: $(w \models \Box\psi) = (\forall v . (v \models \psi))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T7[semantics]$: $(w \models \mathcal{A}\psi) = (dw \models \psi)$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T8\text{-}\nu[semantics]$: $(w \models \forall_\nu x. \psi \ x) = (\forall x . (w \models \psi \ x))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T8\text{-}0[semantics]$: $(w \models \forall_0 x. \psi \ x) = (\forall x . (w \models \psi \ x))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T8\text{-}1[semantics]$: $(w \models \forall_1 x. \psi \ x) = (\forall x . (w \models \psi \ x))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T8\text{-}2[semantics]$: $(w \models \forall_2 x. \psi \ x) = (\forall x . (w \models \psi \ x))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T8\text{-}3[semantics]$: $(w \models \forall_3 x. \psi \ x) = (\forall x . (w \models \psi \ x))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

lemma $T8\text{-}o[semantics]$: $(w \models \forall_o x. \psi \ x) = (\forall x . (w \models \psi \ x))$

by ($simp$ add: $meta\text{-defs}$ $meta\text{-aux}$)

Semantics for descriptions and lambda expressions.

lemma *D3[semantics]*:

$d_\kappa (\iota x . \psi x) = (\text{if } (\exists x . (w_0 \models \psi x) \wedge (\forall y . (w_0 \models \psi y) \longrightarrow y = x))$
 $\text{then } (\text{Some } (\text{THE } x . (w_0 \models \psi x))) \text{ else None})$

unfolding *semantics-defs*

by (*auto simp: meta-defs meta-aux*)

lemma *D4-1[semantics]*: $d_1 (\lambda x . \langle F, x^P \rangle) = d_1 F$

by (*simp add: meta-defs meta-aux*)

lemma *D4-2[semantics]*: $d_2 (\lambda^2 (\lambda x y . \langle F, x^P, y^P \rangle)) = d_2 F$

by (*simp add: meta-defs meta-aux*)

lemma *D4-3[semantics]*: $d_3 (\lambda^3 (\lambda x y z . \langle F, x^P, y^P, z^P \rangle)) = d_3 F$

by (*simp add: meta-defs meta-aux*)

lemma *D5-1[semantics]*:

assumes *IsPropositionalInX* φ

shows $\bigwedge w o_1 r . \text{Some } r = d_1 (\lambda x . (\varphi (x^P))) \wedge \text{Some } o_1 = d_\kappa x$
 $\longrightarrow (o_1 \in \text{ex1 } r w) = (w \models \varphi x)$

using *assms unfolding IsPropositionalIn-defs semantics-defs*

by (*auto simp: meta-defs meta-aux denotes-def denotation-def*)

lemma *D5-2[semantics]*:

assumes *IsPropositionalInXY* φ

shows $\bigwedge w o_1 o_2 r . \text{Some } r = d_2 (\lambda^2 (\lambda x y . \varphi (x^P) (y^P)))$
 $\wedge \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y$
 $\longrightarrow ((o_1, o_2) \in \text{ex2 } r w) = (w \models \varphi x y)$

using *assms unfolding IsPropositionalIn-defs semantics-defs*

by (*auto simp: meta-defs meta-aux denotes-def denotation-def*)

lemma *D5-3[semantics]*:

assumes *IsPropositionalInXYZ* φ

shows $\bigwedge w o_1 o_2 o_3 r . \text{Some } r = d_3 (\lambda^3 (\lambda x y z . \varphi (x^P) (y^P) (z^P)))$
 $\wedge \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y \wedge \text{Some } o_3 = d_\kappa z$
 $\longrightarrow ((o_1, o_2, o_3) \in \text{ex3 } r w) = (w \models \varphi x y z)$

using *assms unfolding IsPropositionalIn-defs semantics-defs*

by (*auto simp: meta-defs meta-aux denotes-def denotation-def*)

lemma *D6[semantics]*: $(\bigwedge w r . \text{Some } r = d_0 (\lambda^0 \varphi) \longrightarrow \text{ex0 } r w = (w \models \varphi))$

by (*auto simp: meta-defs meta-aux semantics-defs*)

Auxiliary lemmata.

lemma *prope_{x1}*: $\exists r . \text{Some } r = d_1 F$

unfolding *d₁-def* **by** *simp*

lemma *d₁-inject*: $\bigwedge x y . d_1 x = d_1 y \implies x = y$

unfolding *d₁-def* **by** (*simp add: eval_{Π1}-inject*)

lemma *d_κ-inject*: $\bigwedge x y o_1 . \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_1 = d_\kappa y \implies x = y$

proof –

fix $x :: \kappa$ **and** $y :: \kappa$ **and** $o_1 :: \nu$

assume $\text{Some } o_1 = d_\kappa x \wedge \text{Some } o_1 = d_\kappa y$

moreover hence

$\text{fst } (\text{eval } \kappa x) \wedge \text{fst } (\text{eval } \kappa y) \wedge \text{snd } (\text{eval } \kappa x) = o_1 \wedge \text{snd } (\text{eval } \kappa y) = o_1$

unfolding *d_κ-def*

apply *transfer*

apply *simp*

by (*metis option.distinct(1) option.inject*)

ultimately show $x = y$

unfolding *d_κ-def*

apply *transfer*

by *auto*

qed

lemma *d_κ-proper*: $d_\kappa (u^P) = \text{Some } u$

unfolding d_{κ} -def by (simp add: $\nu\kappa$ -def meta-aux)
end

3.3 Validity Syntax

abbreviation *validity-in* :: $\text{o} \Rightarrow i \Rightarrow \text{bool}$ ($[- \text{ in } -] [1]$) **where**
validity-in $\equiv \lambda \varphi v . v \models \varphi$
abbreviation *actual-validity* :: $\text{o} \Rightarrow \text{bool}$ ($[-] [1]$) **where**
actual-validity $\equiv \lambda \varphi . dw \models \varphi$
abbreviation *necessary-validity* :: $\text{o} \Rightarrow \text{bool}$ ($\Box[-] [1]$) **where**
necessary-validity $\equiv \lambda \varphi . \forall v . (v \models \varphi)$

4 MetaSolver

Remark 12. *meta-solver* is a resolution prover that translates expressions in the embedded logic to expressions in the meta-logic as far as possible. The rules for connectives and quantifiers are simple, whereas the rules for exemplification and encoding are more verbose. Furthermore rules for the defined identities are proven. By design the defined identities in the embedded logic coincides with the meta-logical equality.

locale *MetaSolver*

begin

interpretation *Semantics* .

named-theorems *meta-intro*

named-theorems *meta-elim*

named-theorems *meta-subst*

named-theorems *meta-cong*

method *meta-solver* = (assumption | rule *meta-intro*
| erule *meta-elim* | drule *meta-elim* | subst *meta-subst*
| subst (asm) *meta-subst* | (erule *notE*; (meta-solver; fail))
)+

4.1 Rules for Implication

lemma *ImplI*[*meta-intro*]: $([\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v]) \Longrightarrow ([\varphi \rightarrow \psi \text{ in } v])$
by (simp add: *Semantics.T5*)
lemma *ImplE*[*meta-elim*]: $([\varphi \rightarrow \psi \text{ in } v]) \Longrightarrow ([\varphi \text{ in } v] \longrightarrow [\psi \text{ in } v])$
by (simp add: *Semantics.T5*)
lemma *ImplS*[*meta-subst*]: $([\varphi \rightarrow \psi \text{ in } v]) = ([\varphi \text{ in } v] \longrightarrow [\psi \text{ in } v])$
by (simp add: *Semantics.T5*)

4.2 Rules for Negation

lemma *NotI*[*meta-intro*]: $\neg[\varphi \text{ in } v] \Longrightarrow [\neg\varphi \text{ in } v]$
by (simp add: *Semantics.T4*)
lemma *NotE*[*meta-elim*]: $[\neg\varphi \text{ in } v] \Longrightarrow \neg[\varphi \text{ in } v]$
by (simp add: *Semantics.T4*)
lemma *NotS*[*meta-subst*]: $[\neg\varphi \text{ in } v] = (\neg[\varphi \text{ in } v])$
by (simp add: *Semantics.T4*)

4.3 Rules for Conjunction

lemma *ConjI*[*meta-intro*]: $([\varphi \text{ in } v] \wedge [\psi \text{ in } v]) \Longrightarrow [\varphi \ \& \ \psi \text{ in } v]$
by (simp add: *conj-def NotS ImplS*)
lemma *ConjE*[*meta-elim*]: $[\varphi \ \& \ \psi \text{ in } v] \Longrightarrow ([\varphi \text{ in } v] \wedge [\psi \text{ in } v])$
by (simp add: *conj-def NotS ImplS*)
lemma *ConjS*[*meta-subst*]: $[\varphi \ \& \ \psi \text{ in } v] = ([\varphi \text{ in } v] \wedge [\psi \text{ in } v])$
by (simp add: *conj-def NotS ImplS*)

4.4 Rules for Equivalence

lemma *EquivI*[meta-intro]: $([\varphi \text{ in } v] \longleftrightarrow [\psi \text{ in } v]) \implies [\varphi \equiv \psi \text{ in } v]$
by (*simp add: equiv-def NotS ImplS ConjS*)
lemma *EquivE*[meta-elim]: $[\varphi \equiv \psi \text{ in } v] \implies ([\varphi \text{ in } v] \longleftrightarrow [\psi \text{ in } v])$
by (*auto simp: equiv-def NotS ImplS ConjS*)
lemma *EquivS*[meta-subst]: $[\varphi \equiv \psi \text{ in } v] = ([\varphi \text{ in } v] \longleftrightarrow [\psi \text{ in } v])$
by (*auto simp: equiv-def NotS ImplS ConjS*)

4.5 Rules for Disjunction

lemma *DisjI*[meta-intro]: $([\varphi \text{ in } v] \vee [\psi \text{ in } v]) \implies [\varphi \vee \psi \text{ in } v]$
by (*auto simp: disj-def NotS ImplS*)
lemma *DisjE*[meta-elim]: $[\varphi \vee \psi \text{ in } v] \implies ([\varphi \text{ in } v] \vee [\psi \text{ in } v])$
by (*auto simp: disj-def NotS ImplS*)
lemma *DisjS*[meta-subst]: $[\varphi \vee \psi \text{ in } v] = ([\varphi \text{ in } v] \vee [\psi \text{ in } v])$
by (*auto simp: disj-def NotS ImplS*)

4.6 Rules for Necessity

lemma *BoxI*[meta-intro]: $(\bigwedge v. [\varphi \text{ in } v]) \implies [\Box \varphi \text{ in } v]$
by (*simp add: Semantics.T6*)
lemma *BoxE*[meta-elim]: $[\Box \varphi \text{ in } v] \implies (\bigwedge v. [\varphi \text{ in } v])$
by (*simp add: Semantics.T6*)
lemma *BoxS*[meta-subst]: $[\Box \varphi \text{ in } v] = (\forall v. [\varphi \text{ in } v])$
by (*simp add: Semantics.T6*)

4.7 Rules for Possibility

lemma *DiaI*[meta-intro]: $(\exists v. [\varphi \text{ in } v]) \implies [\Diamond \varphi \text{ in } v]$
by (*metis BoxS NotS diamond-def*)
lemma *DiaE*[meta-elim]: $[\Diamond \varphi \text{ in } v] \implies (\exists v. [\varphi \text{ in } v])$
by (*metis BoxS NotS diamond-def*)
lemma *DiaS*[meta-subst]: $[\Diamond \varphi \text{ in } v] = (\exists v. [\varphi \text{ in } v])$
by (*metis BoxS NotS diamond-def*)

4.8 Rules for Quantification

lemma *All_νI*[meta-intro]: $(\bigwedge x::\nu. [\varphi \text{ in } v]) \implies [\forall_{\nu} x. \varphi \text{ in } v]$
by (*auto simp: Semantics.T8-ν*)
lemma *All_νE*[meta-elim]: $[\forall_{\nu} x. \varphi \text{ in } v] \implies (\bigwedge x::\nu. [\varphi \text{ in } v])$
by (*auto simp: Semantics.T8-ν*)
lemma *All_νS*[meta-subst]: $[\forall_{\nu} x. \varphi \text{ in } v] = (\forall x::\nu. [\varphi \text{ in } v])$
by (*auto simp: Semantics.T8-ν*)

lemma *All₀I*[meta-intro]: $(\bigwedge x::\Pi_0. [\varphi \text{ in } v]) \implies [\forall_0 x. \varphi \text{ in } v]$
by (*auto simp: Semantics.T8-0*)
lemma *All₀E*[meta-elim]: $[\forall_0 x. \varphi \text{ in } v] \implies (\bigwedge x::\Pi_0. [\varphi \text{ in } v])$
by (*auto simp: Semantics.T8-0*)
lemma *All₀S*[meta-subst]: $[\forall_0 x. \varphi \text{ in } v] = (\forall x::\Pi_0. [\varphi \text{ in } v])$
by (*auto simp: Semantics.T8-0*)

lemma *All₁I*[meta-intro]: $(\bigwedge x::\Pi_1. [\varphi \text{ in } v]) \implies [\forall_1 x. \varphi \text{ in } v]$
by (*auto simp: Semantics.T8-1*)
lemma *All₁E*[meta-elim]: $[\forall_1 x. \varphi \text{ in } v] \implies (\bigwedge x::\Pi_1. [\varphi \text{ in } v])$
by (*auto simp: Semantics.T8-1*)
lemma *All₁S*[meta-subst]: $[\forall_1 x. \varphi \text{ in } v] = (\forall x::\Pi_1. [\varphi \text{ in } v])$
by (*auto simp: Semantics.T8-1*)

lemma *All₂I*[meta-intro]: $(\bigwedge x::\Pi_2. [\varphi \text{ in } v]) \implies [\forall_2 x. \varphi \text{ in } v]$
by (*auto simp: Semantics.T8-2*)
lemma *All₂E*[meta-elim]: $[\forall_2 x. \varphi \text{ in } v] \implies (\bigwedge x::\Pi_2. [\varphi \text{ in } v])$
by (*auto simp: Semantics.T8-2*)
lemma *All₂S*[meta-subst]: $[\forall_2 x. \varphi \text{ in } v] = (\forall x::\Pi_2. [\varphi \text{ in } v])$

by (auto simp: Semantics.T8-2)

lemma *All₃I*[meta-intro]: $(\bigwedge x::\Pi_3. [\varphi \ x \ in \ v]) \implies [\forall_3 \ x. \ \varphi \ x \ in \ v]$
 by (auto simp: Semantics.T8-3)

lemma *All₃E*[meta-elim]: $[\forall_3 \ x. \ \varphi \ x \ in \ v] \implies (\bigwedge x::\Pi_3. [\varphi \ x \ in \ v])$
 by (auto simp: Semantics.T8-3)

lemma *All₃S*[meta-subst]: $[\forall_3 \ x. \ \varphi \ x \ in \ v] = (\forall x::\Pi_3. [\varphi \ x \ in \ v])$
 by (auto simp: Semantics.T8-3)

4.9 Rules for Actuality

lemma *ActualI*[meta-intro]: $[\varphi \ in \ dw] \implies [\mathcal{A}(\varphi) \ in \ v]$
 by (auto simp: Semantics.T7)

lemma *ActualE*[meta-elim]: $[\mathcal{A}(\varphi) \ in \ v] \implies [\varphi \ in \ dw]$
 by (auto simp: Semantics.T7)

lemma *ActualS*[meta-subst]: $[\mathcal{A}(\varphi) \ in \ v] = [\varphi \ in \ dw]$
 by (auto simp: Semantics.T7)

4.10 Rules for Encoding

lemma *EncI*[meta-intro]:
 assumes $\exists \ r \ o_1. \ Some \ r = d_1 \ F \wedge \ Some \ o_1 = d_\kappa \ x \wedge \ o_1 \in en \ r$
 shows $[\llbracket x, F \rrbracket \ in \ v]$
 using assms by (auto simp: Semantics.T2)

lemma *EncE*[meta-elim]:
 assumes $[\llbracket x, F \rrbracket \ in \ v]$
 shows $\exists \ r \ o_1. \ Some \ r = d_1 \ F \wedge \ Some \ o_1 = d_\kappa \ x \wedge \ o_1 \in en \ r$
 using assms by (auto simp: Semantics.T2)

lemma *EncS*[meta-subst]:
 $[\llbracket x, F \rrbracket \ in \ v] = (\exists \ r \ o_1. \ Some \ r = d_1 \ F \wedge \ Some \ o_1 = d_\kappa \ x \wedge \ o_1 \in en \ r)$
 by (auto simp: Semantics.T2)

4.11 Rules for Exemplification

4.11.1 Zero-place Relations

lemma *Exe0I*[meta-intro]:
 assumes $\exists \ r. \ Some \ r = d_0 \ p \wedge \ ex0 \ r \ v$
 shows $[\llbracket p \rrbracket \ in \ v]$
 using assms by (auto simp: Semantics.T3)

lemma *Exe0E*[meta-elim]:
 assumes $[\llbracket p \rrbracket \ in \ v]$
 shows $\exists \ r. \ Some \ r = d_0 \ p \wedge \ ex0 \ r \ v$
 using assms by (auto simp: Semantics.T3)

lemma *Exe0S*[meta-subst]:
 $[\llbracket p \rrbracket \ in \ v] = (\exists \ r. \ Some \ r = d_0 \ p \wedge \ ex0 \ r \ v)$
 by (auto simp: Semantics.T3)

4.11.2 One-Place Relations

lemma *Exe1I*[meta-intro]:
 assumes $\exists \ r \ o_1. \ Some \ r = d_1 \ F \wedge \ Some \ o_1 = d_\kappa \ x \wedge \ o_1 \in ex1 \ r \ v$
 shows $[\llbracket F, x \rrbracket \ in \ v]$
 using assms by (auto simp: Semantics.T1-1)

lemma *Exe1E*[meta-elim]:
 assumes $[\llbracket F, x \rrbracket \ in \ v]$
 shows $\exists \ r \ o_1. \ Some \ r = d_1 \ F \wedge \ Some \ o_1 = d_\kappa \ x \wedge \ o_1 \in ex1 \ r \ v$
 using assms by (auto simp: Semantics.T1-1)

lemma *Exe1S*[meta-subst]:
 $[\llbracket F, x \rrbracket \ in \ v] = (\exists \ r \ o_1. \ Some \ r = d_1 \ F \wedge \ Some \ o_1 = d_\kappa \ x \wedge \ o_1 \in ex1 \ r \ v)$
 by (auto simp: Semantics.T1-1)

4.11.3 Two-Place Relations

lemma *Exe2I*[meta-intro]:

assumes $\exists r \ o_1 \ o_2 . \text{Some } r = d_2 \ F \wedge \text{Some } o_1 = d_\kappa \ x$
 $\wedge \text{Some } o_2 = d_\kappa \ y \wedge (o_1, o_2) \in \text{ex2 } r \ v$
shows $[\langle F, x, y \rangle \text{ in } v]$
using *assms* **by** (*auto simp: Semantics.T1-2*)
lemma *Exe2E*[*meta-elim*]:
assumes $[\langle F, x, y \rangle \text{ in } v]$
shows $\exists r \ o_1 \ o_2 . \text{Some } r = d_2 \ F \wedge \text{Some } o_1 = d_\kappa \ x$
 $\wedge \text{Some } o_2 = d_\kappa \ y \wedge (o_1, o_2) \in \text{ex2 } r \ v$
using *assms* **by** (*auto simp: Semantics.T1-2*)
lemma *Exe2S*[*meta-subst*]:
 $[\langle F, x, y \rangle \text{ in } v] = (\exists r \ o_1 \ o_2 . \text{Some } r = d_2 \ F \wedge \text{Some } o_1 = d_\kappa \ x$
 $\wedge \text{Some } o_2 = d_\kappa \ y \wedge (o_1, o_2) \in \text{ex2 } r \ v)$
by (*auto simp: Semantics.T1-2*)

4.11.4 Three-Place Relations

lemma *Exe3I*[*meta-intro*]:
assumes $\exists r \ o_1 \ o_2 \ o_3 . \text{Some } r = d_3 \ F \wedge \text{Some } o_1 = d_\kappa \ x$
 $\wedge \text{Some } o_2 = d_\kappa \ y \wedge \text{Some } o_3 = d_\kappa \ z$
 $\wedge (o_1, o_2, o_3) \in \text{ex3 } r \ v$
shows $[\langle F, x, y, z \rangle \text{ in } v]$
using *assms* **by** (*auto simp: Semantics.T1-3*)
lemma *Exe3E*[*meta-elim*]:
assumes $[\langle F, x, y, z \rangle \text{ in } v]$
shows $\exists r \ o_1 \ o_2 \ o_3 . \text{Some } r = d_3 \ F \wedge \text{Some } o_1 = d_\kappa \ x$
 $\wedge \text{Some } o_2 = d_\kappa \ y \wedge \text{Some } o_3 = d_\kappa \ z$
 $\wedge (o_1, o_2, o_3) \in \text{ex3 } r \ v$
using *assms* **by** (*auto simp: Semantics.T1-3*)
lemma *Exe3S*[*meta-subst*]:
 $[\langle F, x, y, z \rangle \text{ in } v] = (\exists r \ o_1 \ o_2 \ o_3 . \text{Some } r = d_3 \ F \wedge \text{Some } o_1 = d_\kappa \ x$
 $\wedge \text{Some } o_2 = d_\kappa \ y \wedge \text{Some } o_3 = d_\kappa \ z$
 $\wedge (o_1, o_2, o_3) \in \text{ex3 } r \ v)$
by (*auto simp: Semantics.T1-3*)

4.12 Rules for Being Ordinary

lemma *OrdI*[*meta-intro*]:
assumes $\exists o_1 \ y . \text{Some } o_1 = d_\kappa \ x \wedge o_1 = \omega\nu \ y$
shows $[\langle O!, x \rangle \text{ in } v]$
proof –
obtain o_1 **and** y **where** $1: \text{Some } o_1 = d_\kappa \ x \wedge o_1 = \omega\nu \ y$
using *assms* **by** *auto*
moreover obtain v **where** *ConcreteInWorld* $y \ v$
using *OrdinaryObjectsPossiblyConcreteAxiom* **by** *auto*
ultimately show *?thesis*
unfolding *Ordinary-def conn-defs meta-defs*
apply (*simp add: meta-aux*)
apply *transfer*
by (*metis* (*full-types*) *$\nu\nu\text{-}\omega\nu\text{-is-}\omega\nu$* *$v.\text{simsps}(5)$*
 $\text{option.distinct}(1)$ *option.sel*)
qed
lemma *OrdE*[*meta-elim*]:
assumes $[\langle O!, x \rangle \text{ in } v]$
shows $\exists o_1 \ y . \text{Some } o_1 = d_\kappa \ x \wedge o_1 = \omega\nu \ y$
using *assms* **unfolding** *Ordinary-def conn-defs meta-defs*
apply (*simp add: meta-aux $d_\kappa\text{-def denotes-def denotation-def}$*)
by (*metis* *$v.\text{exhaust}$* *$v.\text{simsps}(6)$* *$\nu\nu\text{-def}$* *$v.\text{simsps}(6)$* *comp-apply*)
lemma *OrdS*[*meta-cong*]:
 $[\langle O!, x \rangle \text{ in } v] = (\exists o_1 \ y . \text{Some } o_1 = d_\kappa \ x \wedge o_1 = \omega\nu \ y)$
using *OrdI OrdE* **by** *blast*

4.13 Rules for Being Abstract

lemma *AbsI*[*meta-intro*]:

```

assumes  $\exists o_1 y. \text{Some } o_1 = d_\kappa x \wedge o_1 = \alpha\nu y$ 
shows  $[(A!,x)] \text{ in } v$ 
proof –
  obtain  $o_1 y$  where  $\text{Some } o_1 = d_\kappa x \wedge o_1 = \alpha\nu y$ 
  using assms by auto
thus ?thesis
  unfolding Abstract-def conn-defs meta-defs
  apply (simp add: meta-aux)
  by (metis d $\kappa$ -inject d $\kappa$ -proper  $\nu$ .simps(6)  $\nu\nu$ -def  $\nu$ .simps(6)
      o-apply proper-denotation proper-denotes)
qed
lemma AbsE[meta-elim]:
  assumes  $[(A!,x)] \text{ in } v$ 
  shows  $\exists o_1 y. \text{Some } o_1 = d_\kappa x \wedge o_1 = \alpha\nu y$ 
  using assms unfolding conn-defs meta-defs Abstract-def
  apply (simp add: meta-aux d $\kappa$ -def denotes-def denotation-def)
  by (metis OrdinaryObjectsPossiblyConcreteAxiom  $\nu$ .exhaust
       $\nu\nu$ - $\omega\nu$ -is- $\omega\nu$   $\nu$ .simps(5)))
lemma AbsS[meta-cong]:
   $[(A!,x)] \text{ in } v = (\exists o_1 y. \text{Some } o_1 = d_\kappa x \wedge o_1 = \alpha\nu y)$ 
  using AbsI AbsE by blast

```

4.14 Rules for Definite Descriptions

```

lemma TheS:  $(\iota x. \varphi x) = \text{make}\kappa (\exists! x . \text{evalo } (\varphi x) \text{ dj } dw,$ 
       $\text{THE } x . \text{evalo } (\varphi x) \text{ dj } dw)$ 
by (auto simp: meta-defs)

```

4.15 Rules for Identity

4.15.1 Ordinary Objects

```

lemma EqEI[meta-intro]:
  assumes  $\exists o_1 X o_2. \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y \wedge o_1 = o_2 \wedge o_1 = \omega\nu X$ 
  shows  $[x =_E y] \text{ in } v$ 
  using assms
  apply (simp add: meta-defs meta-aux basic-identityE-def basic-identityE-infix-def
      conn-defs Ordinary-def OrdinaryObjectsPossiblyConcreteAxiom
      denotes-def Semantics.d $\kappa$ -def
      split:  $\nu$ .split  $\nu$ .split)
  using OrdinaryObjectsPossiblyConcreteAxiom
  apply transfer
  apply simp
  by (metis  $\nu\nu$ - $\omega\nu$ -is- $\omega\nu$   $\nu$ .distinct(1)  $\nu$ .inject(1) option.distinct(1) option.sel)
lemma EqEE[meta-elim]:
  assumes  $[x =_E y] \text{ in } v$ 
  shows  $\exists o_1 X o_2. \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y \wedge o_1 = o_2 \wedge o_1 = \omega\nu X$ 
proof –
  have 1:  $[(O!,x)] \ \& \ [(O!,y)] \ \& \ \Box(\forall_1 F. [(F,x)] \equiv [(F,y)]) \text{ in } v$ 
  using assms unfolding basic-identityE-def basic-identityE-infix-def
  using D4-2 T1-2 D5-2 IsPropositional-intros by meson
  hence 2:  $\exists o_1 o_2 X Y . \text{Some } o_1 = d_\kappa x \wedge o_1 = \omega\nu X$ 
       $\wedge \text{Some } o_2 = d_\kappa y \wedge o_2 = \omega\nu Y$ 
  apply (subst (asm) ConjS)
  apply (subst (asm) ConjS)
  using OrdE by auto
  then obtain  $o_1 o_2 X Y$  where 3:
       $\text{Some } o_1 = d_\kappa x \wedge o_1 = \omega\nu X \wedge \text{Some } o_2 = d_\kappa y \wedge o_2 = \omega\nu Y$ 
  by auto
  have  $\exists r . \text{Some } r = d_1 (\lambda z . \text{makeo } (\lambda w s . d_\kappa (z^P) = \text{Some } o_1))$ 
  using propex1 by auto
  then obtain  $r$  where 4:
       $\text{Some } r = d_1 (\lambda z . \text{makeo } (\lambda w s . d_\kappa (z^P) = \text{Some } o_1))$ 
  by auto

```

hence 5: $r = (\lambda u \ w \ s. \text{Some } (v\nu \ u) = \text{Some } o_1)$
 unfolding *lambdabinder1-def d₁-def d_κ-proper*
 apply *transfer*
 by *simp*
 have $\Box(\forall_1 F. \langle F, x \rangle \equiv \langle F, y \rangle)$ in v
 using 1 using *ConjE* by *blast*
 hence 6: $\forall v \ F. [\langle F, x \rangle \text{ in } v] \longleftrightarrow [\langle F, y \rangle \text{ in } v]$
 using *BoxE EquivE All₁E* by *fast*
 hence 7: $\forall v. (o_1 \in \text{ex1 } r \ v) = (o_2 \in \text{ex1 } r \ v)$
 using 2 4 unfolding *valid-in-def*
 by (*metis* 3 6 *d₁.rep-eq d_κ-inject d_κ-proper ex1-def evalo-inverse exe1.rep-eq*
mem-Collect-eq option.sel proper-denotation proper-denotes valid-in.abs-eq)
 have $o_1 \in \text{ex1 } r \ v$
 using 5 3 unfolding *ex1-def* by (*simp add: meta-ax*)
 hence $o_2 \in \text{ex1 } r \ v$
 using 7 by *auto*
 hence $o_1 = o_2$
 unfolding *ex1-def* 5 using 3 by (*auto simp: meta-ax*)
 thus ?thesis
 using 3 by *auto*
 qed — TODO: simplify this
 lemma *Eq_ES[meta-subst]*:
 $[x =_E y \text{ in } v] = (\exists o_1 \ X \ o_2. \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y$
 $\wedge o_1 = o_2 \wedge o_1 = \omega\nu \ X)$
 using *Eq_EI Eq_EE* by *blast*

4.15.2 Individuals

lemma *Eq_κI[meta-intro]*:
 assumes $\exists o_1 \ o_2. \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y \wedge o_1 = o_2$
 shows $[x =_\kappa y \text{ in } v]$
 proof —
 have $x = y$ using *assms d_κ-inject* by *meson*
 moreover have $[x =_\kappa x \text{ in } v]$
 unfolding *basic-identity_κ-def*
 apply *meta-solver*
 by (*metis* (*no-types, lifting*) *assms AbsI Exe1E ν.exhaust*)
 ultimately show ?thesis by *auto*
 qed
 lemma *Eq_κ-prop*:
 assumes $[x =_\kappa y \text{ in } v]$
 shows $[\varphi \ x \text{ in } v] = [\varphi \ y \text{ in } v]$
 proof —
 have $[x =_E y \vee (\langle A!, x \rangle \ \& \ \langle A!, y \rangle) \ \& \ \Box(\forall_1 F. \langle x, F \rangle \equiv \langle y, F \rangle)]$ in v
 using *assms unfolding basic-identity_κ-def* by *simp*
 moreover {
 assume $[x =_E y \text{ in } v]$
 hence $(\exists o_1 \ o_2. \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y \wedge o_1 = o_2)$
 using *Eq_EE* by *fast*
 }
 moreover {
 assume 1: $[(\langle A!, x \rangle \ \& \ \langle A!, y \rangle) \ \& \ \Box(\forall_1 F. \langle x, F \rangle \equiv \langle y, F \rangle)]$ in v
 hence 2: $(\exists o_1 \ o_2 \ X \ Y. \text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y$
 $\wedge o_1 = \alpha\nu \ X \wedge o_2 = \alpha\nu \ Y)$
 using *AbsE ConjE* by *meson*
 moreover then obtain $o_1 \ o_2 \ X \ Y$ where 3:
 $\text{Some } o_1 = d_\kappa x \wedge \text{Some } o_2 = d_\kappa y \wedge o_1 = \alpha\nu \ X \wedge o_2 = \alpha\nu \ Y$
 by *auto*
 moreover have 4: $[\Box(\forall_1 F. \langle x, F \rangle \equiv \langle y, F \rangle)]$ in v
 using 1 *ConjE* by *blast*
 hence 6: $\forall v \ F. [\langle x, F \rangle \text{ in } v] \longleftrightarrow [\langle y, F \rangle \text{ in } v]$
 using *BoxE All₁E EquivE* by *fast*
 hence 7: $\forall v \ r. (\exists o_1. \text{Some } o_1 = d_\kappa x \wedge o_1 \in \text{en } r)$
 $= (\exists o_1. \text{Some } o_1 = d_\kappa y \wedge o_1 \in \text{en } r)$

```

    apply cut-tac apply meta-solver
    using properx d1-inject apply simp
    apply transfer by simp
  hence  $\delta: \forall r. (o_1 \in en\ r) = (o_2 \in en\ r)$ 
    using  $\mathcal{J}$  d $\kappa$ -inject d $\kappa$ -proper apply simp
    by (metis option.inject)
  hence  $\forall r. (o_1 \in r) = (o_2 \in r)$ 
    unfolding en-def using  $\mathcal{J}$ 
    by (metis Collect-cong Collect-mem-eq v.simps(6)
        mem-Collect-eq make $\Pi_1$ -cases)
  hence  $(o_1 \in \{x \mid o_1 = x\}) = (o_2 \in \{x \mid o_1 = x\})$ 
    by metis
  hence  $o_1 = o_2$  by simp
  hence  $(\exists o_1\ o_2. \text{Some } o_1 = d_\kappa\ x \wedge \text{Some } o_2 = d_\kappa\ y \wedge o_1 = o_2)$ 
    using  $\mathcal{J}$  by auto
}
ultimately have  $x = y$ 
  using DisjS using Semantics.d $\kappa$ -inject by auto
thus  $(v \models (\varphi\ x)) = (v \models (\varphi\ y))$  by simp
qed
lemma Eq $\kappa$ E[meta-elim]:
  assumes  $[x =_\kappa y\ \text{in } v]$ 
  shows  $\exists o_1\ o_2. \text{Some } o_1 = d_\kappa\ x \wedge \text{Some } o_2 = d_\kappa\ y \wedge o_1 = o_2$ 
proof -
  have  $\forall \varphi. (v \models \varphi\ x) = (v \models \varphi\ y)$ 
    using assms Eq $\kappa$ -prop by blast
  moreover obtain  $\varphi$  where  $\varphi$ -prop:
     $\varphi = (\lambda \alpha. \text{makeo } (\lambda w\ s. (\exists o_1\ o_2. \text{Some } o_1 = d_\kappa\ x \wedge \text{Some } o_2 = d_\kappa\ \alpha \wedge o_1 = o_2)))$ 
    by auto
  ultimately have  $(v \models \varphi\ x) = (v \models \varphi\ y)$  by metis
  moreover have  $(v \models \varphi\ x)$ 
    using assms unfolding  $\varphi$ -prop basic-identity $\kappa$ -def
    by (metis (mono-tags, lifting) AbsS ConjE DisjS
        EqES valid-in.abs-eq)
  ultimately have  $(v \models \varphi\ y)$  by auto
  thus ?thesis
    unfolding  $\varphi$ -prop
    by (simp add: valid-in-def meta-aux)
qed
lemma Eq $\kappa$ S[meta-subst]:
   $[x =_\kappa y\ \text{in } v] = (\exists o_1\ o_2. \text{Some } o_1 = d_\kappa\ x \wedge \text{Some } o_2 = d_\kappa\ y \wedge o_1 = o_2)$ 
  using Eq $\kappa$ I Eq $\kappa$ E by blast

```

4.15.3 One-Place Relations

```

lemma Eq1I[meta-intro]:  $F = G \implies [F =_1 G\ \text{in } v]$ 
  unfolding basic-identity1-def
  apply (rule BoxI, rule AllvI, rule EquivI)
  by simp
lemma Eq1E[meta-elim]:  $[F =_1 G\ \text{in } v] \implies F = G$ 
  unfolding basic-identity1-def
  apply (drule BoxE, drule-tac  $x = (\alpha v\ \{F\})$  in AllvE, drule EquivE)
  apply (simp add: Semantics.T2)
  unfolding en-def d $\kappa$ -def d1-def
  using proper-denotation proper-denotes
  by (simp add: denotation-def denotes-def meta-aux)
lemma Eq1S[meta-subst]:  $[F =_1 G\ \text{in } v] = (F = G)$ 
  using Eq1I Eq1E by auto
lemma Eq1-prop:  $[F =_1 G\ \text{in } v] \implies [\varphi\ F\ \text{in } v] = [\varphi\ G\ \text{in } v]$ 
  using Eq1E by blast

```

4.15.4 Two-Place Relations

lemma $Eq_2I[meta-intro]$: $F = G \implies [F =_2 G \text{ in } v]$
unfolding *basic-identity₂-def*
apply (*rule All_vI*, *rule ConjI*, (*subst Eq₁S*)+)
by *simp*
lemma $Eq_2E[meta-elim]$: $[F =_2 G \text{ in } v] \implies F = G$
proof –
assume $[F =_2 G \text{ in } v]$
hence $[\forall_{\nu} x. (\lambda y. \langle F, x^P, y^P \rangle) =_1 (\lambda y. \langle G, x^P, y^P \rangle)] \text{ in } v$
unfolding *basic-identity₂-def*
apply *cut-tac* **apply** *meta-solver* **by** *auto*
hence $\bigwedge x. (make\Pi_1 (eval\Pi_2 F (\nu v x)) = make\Pi_1 ((eval\Pi_2 G (\nu v x))))$
apply *cut-tac* **apply** *meta-solver*
by (*simp add: meta-defs meta-aux*)
hence $\bigwedge x. (eval\Pi_2 F (\nu v x) = eval\Pi_2 G (\nu v x))$
by (*simp add: make\Pi₁-inject*)
hence $\bigwedge x1. (eval\Pi_2 F x1 = eval\Pi_2 G x1)$
using *νv -surj* **by** (*metis νv - νv -id*)
thus $F = G$ **using** *eval\Pi₂-inject* **by** *blast*
qed
lemma $Eq_2S[meta-subst]$: $[F =_2 G \text{ in } v] = (F = G)$
using Eq_2I Eq_2E **by** *auto*
lemma Eq_2-prop : $[F =_2 G \text{ in } v] \implies [\varphi F \text{ in } v] = [\varphi G \text{ in } v]$
using Eq_2E **by** *blast*

4.15.5 Three-Place Relations

lemma $Eq_3I[meta-intro]$: $F = G \implies [F =_3 G \text{ in } v]$
apply (*simp add: meta-defs meta-aux conn-defs basic-identity₃-def*)
using *MetaSolver.Eq₁I valid-in.rep-eq* **by** *auto*
lemma $Eq_3E[meta-elim]$: $[F =_3 G \text{ in } v] \implies F = G$
proof –
assume $[F =_3 G \text{ in } v]$
hence $[\forall_{\nu} x y. (\lambda z. \langle F, x^P, y^P, z^P \rangle) =_1 (\lambda z. \langle G, x^P, y^P, z^P \rangle)] \text{ in } v$
unfolding *basic-identity₃-def* **apply** *cut-tac*
apply *meta-solver* **by** *auto*
hence $\bigwedge x y. (\lambda z. \langle F, x^P, y^P, z^P \rangle) = (\lambda z. \langle G, x^P, y^P, z^P \rangle)$
using Eq_1E *All_vS* **by** (*metis (mono-tags, lifting)*)
hence $\bigwedge x y. make\Pi_1 (eval\Pi_3 F x y) = make\Pi_1 (eval\Pi_3 G x y)$
apply (*auto simp: meta-defs meta-aux*)
using *νv -surj* **by** (*metis νv - νv -id*)
thus $F = G$ **using** *make\Pi₁-inject eval\Pi₃-inject* **by** *blast*
qed
lemma $Eq_3S[meta-subst]$: $[F =_3 G \text{ in } v] = (F = G)$
using Eq_3I Eq_3E **by** *auto*
lemma Eq_3-prop : $[F =_3 G \text{ in } v] \implies [\varphi F \text{ in } v] = [\varphi G \text{ in } v]$
using Eq_3E **by** *blast*

4.15.6 Propositions

lemma $Eq_oI[meta-intro]$: $x = y \implies [x =_o y \text{ in } v]$
unfolding *basic-identity_o-def* **by** (*simp add: Eq₁S*)
lemma $Eq_oE[meta-elim]$: $[F =_o G \text{ in } v] \implies F = G$
unfolding *basic-identity_o-def*
apply (*drule Eq₁E*)
apply (*simp add: meta-defs*)
using *evalo-inject make\Pi₁-inject*
by (*metis UNIV-I*)
lemma $Eq_oS[meta-subst]$: $[F =_o G \text{ in } v] = (F = G)$
using Eq_oI Eq_oE **by** *auto*
lemma Eq_o-prop : $[F =_o G \text{ in } v] \implies [\varphi F \text{ in } v] = [\varphi G \text{ in } v]$
using Eq_oE **by** *blast*

end

5 General Quantification

Remark 13. *In order to define general quantifiers that can act on all variable types a type class is introduced which assumes the semantics of the all quantifier. This type class is then instantiated for all variable types.*

5.1 Type Class

Datatype for types for which quantification is defined:

```
datatype var = νvar (varν: ν) | ovar (varo: o) | Π1var (varΠ1: Π1)
           | Π2var (varΠ2: Π2) | Π3var (varΠ3: Π3)
```

Type class for quantifiable types:

```
class quantifiable = fixes forall :: ('a⇒o)⇒o (binder ∀ [8] 9)
                  and qvar :: 'a⇒var
                  and varq :: var⇒'a
assumes quantifiable-T8: (w ⊨ (∀ x . ψ x)) = (∀ x . (w ⊨ (ψ x)))
and varq-qvar-id: varq (qvar x) = x
begin
definition exists :: ('a⇒o)⇒o (binder ∃ [8] 9) where
  exists ≡ λ φ . ¬(∀ x . ¬φ x)
declare exists-def[conn-defs]
end
```

Semantics for the general all quantifier:

```
lemma (in Semantics) T8: shows (w ⊨ ∀ x . ψ x) = (∀ x . (w ⊨ ψ x))
using quantifiable-T8 .
```

5.2 Instantiations

```
instantiation ν :: quantifiable
begin
definition forall-ν :: (ν⇒o)⇒o where forall-ν ≡ forallν
definition qvar-ν :: ν⇒var where qvar ≡ νvar
definition varq-ν :: var⇒ν where varq ≡ varν
instance proof
  fix w :: i and ψ :: ν⇒o
  show (w ⊨ ∀ x. ψ x) = (∀ x. (w ⊨ ψ x))
    unfolding forall-ν-def using Semantics.T8-ν .
next
  fix x :: ν
  show varq (qvar x) = x
    unfolding qvar-ν-def varq-ν-def by simp
qed
end
```

```
instantiation o :: quantifiable
begin
definition forall-o :: (o⇒o)⇒o where forall-o ≡ forallo
definition qvar-o :: o⇒var where qvar ≡ ovar
definition varq-o :: var⇒o where varq ≡ varo
instance proof
  fix w :: i and ψ :: o⇒o
  show (w ⊨ ∀ x. ψ x) = (∀ x. (w ⊨ ψ x))
    unfolding forall-o-def using Semantics.T8-o .
next
  fix x :: o
```

```

  show varq (qvar x) = x
  unfolding qvar-o-def varq-o-def by simp
qed
end

instantiation  $\Pi_1 :: \text{quantifiable}$ 
begin
  definition forall- $\Pi_1 :: (\Pi_1 \Rightarrow o) \Rightarrow o$  where forall- $\Pi_1 \equiv \text{forall}_1$ 
  definition qvar- $\Pi_1 :: \Pi_1 \Rightarrow \text{var}$  where qvar  $\equiv \Pi_1 \text{ var}$ 
  definition varq- $\Pi_1 :: \text{var} \Rightarrow \Pi_1$  where varq  $\equiv \text{var} \Pi_1$ 
  instance proof
    fix w :: i and  $\psi :: \Pi_1 \Rightarrow o$ 
    show (w  $\models \forall x. \psi x$ ) = ( $\forall x. (w \models \psi x)$ )
      unfolding forall- $\Pi_1$ -def using Semantics.T8-1 .
  next
    fix x ::  $\Pi_1$ 
    show varq (qvar x) = x
      unfolding qvar- $\Pi_1$ -def varq- $\Pi_1$ -def by simp
  qed
end

```

```

instantiation  $\Pi_2 :: \text{quantifiable}$ 
begin
  definition forall- $\Pi_2 :: (\Pi_2 \Rightarrow o) \Rightarrow o$  where forall- $\Pi_2 \equiv \text{forall}_2$ 
  definition qvar- $\Pi_2 :: \Pi_2 \Rightarrow \text{var}$  where qvar  $\equiv \Pi_2 \text{ var}$ 
  definition varq- $\Pi_2 :: \text{var} \Rightarrow \Pi_2$  where varq  $\equiv \text{var} \Pi_2$ 
  instance proof
    fix w :: i and  $\psi :: \Pi_2 \Rightarrow o$ 
    show (w  $\models \forall x. \psi x$ ) = ( $\forall x. (w \models \psi x)$ )
      unfolding forall- $\Pi_2$ -def using Semantics.T8-2 .
  next
    fix x ::  $\Pi_2$ 
    show varq (qvar x) = x
      unfolding qvar- $\Pi_2$ -def varq- $\Pi_2$ -def by simp
  qed
end

```

```

instantiation  $\Pi_3 :: \text{quantifiable}$ 
begin
  definition forall- $\Pi_3 :: (\Pi_3 \Rightarrow o) \Rightarrow o$  where forall- $\Pi_3 \equiv \text{forall}_3$ 
  definition qvar- $\Pi_3 :: \Pi_3 \Rightarrow \text{var}$  where qvar  $\equiv \Pi_3 \text{ var}$ 
  definition varq- $\Pi_3 :: \text{var} \Rightarrow \Pi_3$  where varq  $\equiv \text{var} \Pi_3$ 
  instance proof
    fix w :: i and  $\psi :: \Pi_3 \Rightarrow o$ 
    show (w  $\models \forall x. \psi x$ ) = ( $\forall x. (w \models \psi x)$ )
      unfolding forall- $\Pi_3$ -def using Semantics.T8-3 .
  next
    fix x ::  $\Pi_3$ 
    show varq (qvar x) = x
      unfolding qvar- $\Pi_3$ -def varq- $\Pi_3$ -def by simp
  qed
end

```

5.3 MetaSolver Rules

Remark 14. *The meta-solver is extended by rules for general quantification.*

```

context MetaSolver
begin

```

5.3.1 Rules for General All Quantification.

```

lemma AllI[meta-intro]: ( $\bigwedge x :: 'a :: \text{quantifiable}. [\varphi x \text{ in } v]$ )  $\implies [\forall x. \varphi x \text{ in } v]$ 
  by (auto simp: Semantics.T8)

```

```

lemma Alle[meta-elim]:  $[\forall x. \varphi \ x \text{ in } v] \implies (\bigwedge x::'a::\text{quantifiable}. [\varphi \ x \text{ in } v])$ 
  by (auto simp: Semantics.T8)
lemma AllS[meta-subst]:  $[\forall x. \varphi \ x \text{ in } v] = (\forall x::'a::\text{quantifiable}. [\varphi \ x \text{ in } v])$ 
  by (auto simp: Semantics.T8)

```

5.3.2 Rules for Existence

```

lemma ExIRule:  $([\varphi \ y \text{ in } v]) \implies [\exists x. \varphi \ x \text{ in } v]$ 
  by (auto simp: exists-def NotS AllS)
lemma ExI[meta-intro]:  $(\exists y. [\varphi \ y \text{ in } v]) \implies [\exists x. \varphi \ x \text{ in } v]$ 
  by (auto simp: exists-def NotS AllS)
lemma ExE[meta-elim]:  $[\exists x. \varphi \ x \text{ in } v] \implies (\exists y. [\varphi \ y \text{ in } v])$ 
  by (auto simp: exists-def NotS AllS)
lemma ExS[meta-subst]:  $[\exists x. \varphi \ x \text{ in } v] = (\exists y. [\varphi \ y \text{ in } v])$ 
  by (auto simp: exists-def NotS AllS)
lemma ExERule: assumes  $[\exists x. \varphi \ x \text{ in } v]$  obtains  $x$  where  $[\varphi \ x \text{ in } v]$ 
  using ExE assms by auto

```

end

6 General Identity

Remark 15. In order to define a general identity symbol that can act on all types of terms a type class is introduced which assumes the substitution property of equality which is needed to state the axioms later. This type class is then instantiated for all applicable types.

6.1 Type Classes

```

class identifiable =
fixes identity :: 'a  $\Rightarrow$  'a  $\Rightarrow$  o (infixl = 63)
assumes l-identity:
   $w \models x = y \implies w \models \varphi \ x \implies w \models \varphi \ y$ 
begin
  abbreviation notequal (infixl  $\neq$  63) where
    notequal  $\equiv \lambda x \ y. \neg(x = y)$ 
end

class quantifiable-and-identifiable = quantifiable + identifiable
begin
  definition exists-unique::('a  $\Rightarrow$  o)  $\Rightarrow$  o (binder  $\exists!$  [8] 9) where
    exists-unique  $\equiv \lambda \varphi. \exists \alpha. \varphi \ \alpha \ \& \ (\forall \beta. \varphi \ \beta \rightarrow \beta = \alpha)$ 

  declare exists-unique-def[conn-defs]
end

```

6.2 Instantiations

```

instantiation  $\kappa$  :: identifiable
begin
  definition identity- $\kappa$  where identity- $\kappa \equiv \text{basic-identity}_\kappa$ 
  instance proof
    fix  $x \ y :: \kappa$  and  $w \ \varphi$ 
    show  $[x = y \text{ in } w] \implies [\varphi \ x \text{ in } w] \implies [\varphi \ y \text{ in } w]$ 
      unfolding identity- $\kappa$ -def
      using MetaSolver.Eq $\kappa$ -prop ..
    qed
end

instantiation  $\nu$  :: identifiable
begin
  definition identity- $\nu$  where identity- $\nu \equiv \lambda x \ y. x^P = y^P$ 

```



```

instance proof
  fix  $\alpha :: \nu$  and  $\beta :: \nu$  and  $v \varphi$ 
  assume  $v \models \alpha = \beta$ 
  hence  $v \models \alpha^P = \beta^P$ 
    unfolding identity- $\nu$ -def by auto
  hence  $\bigwedge \varphi. (v \models \varphi (\alpha^P)) \implies (v \models \varphi (\beta^P))$ 
    using l-identity by auto
  hence  $(v \models \varphi (\text{denotation } (\alpha^P))) \implies (v \models \varphi (\text{denotation } (\beta^P)))$ 
    by meson
  thus  $(v \models \varphi \alpha) \implies (v \models \varphi \beta)$ 
    by (simp only: proper-denotation)
qed
end

instantiation  $\Pi_1 :: \text{identifiable}$ 
begin
  definition identity- $\Pi_1$  where identity- $\Pi_1 \equiv \text{basic-identity}_1$ 
  instance proof
    fix  $F G :: \Pi_1$  and  $w \varphi$ 
    show  $(w \models F = G) \implies (w \models \varphi F) \implies (w \models \varphi G)$ 
      unfolding identity- $\Pi_1$ -def using MetaSolver.Eq1-prop ..
    qed
  end

  instantiation  $\Pi_2 :: \text{identifiable}$ 
  begin
    definition identity- $\Pi_2$  where identity- $\Pi_2 \equiv \text{basic-identity}_2$ 
    instance proof
      fix  $F G :: \Pi_2$  and  $w \varphi$ 
      show  $(w \models F = G) \implies (w \models \varphi F) \implies (w \models \varphi G)$ 
        unfolding identity- $\Pi_2$ -def using MetaSolver.Eq2-prop ..
      qed
    end

    instantiation  $\Pi_3 :: \text{identifiable}$ 
    begin
      definition identity- $\Pi_3$  where identity- $\Pi_3 \equiv \text{basic-identity}_3$ 
      instance proof
        fix  $F G :: \Pi_3$  and  $w \varphi$ 
        show  $(w \models F = G) \implies (w \models \varphi F) \implies (w \models \varphi G)$ 
          unfolding identity- $\Pi_3$ -def using MetaSolver.Eq3-prop ..
        qed
      end

      instantiation  $\circ :: \text{identifiable}$ 
      begin
        definition identity- $\circ$  where identity- $\circ \equiv \text{basic-identity}_\circ$ 
        instance proof
          fix  $F G :: \circ$  and  $w \varphi$ 
          show  $(w \models F = G) \implies (w \models \varphi F) \implies (w \models \varphi G)$ 
            unfolding identity- $\circ$ -def using MetaSolver.Eq $\circ$ -prop ..
          qed
        end

        instance  $\nu :: \text{quantifiable-and-identifiable} ..$ 
        instance  $\Pi_1 :: \text{quantifiable-and-identifiable} ..$ 
        instance  $\Pi_2 :: \text{quantifiable-and-identifiable} ..$ 
        instance  $\Pi_3 :: \text{quantifiable-and-identifiable} ..$ 
        instance  $\circ :: \text{quantifiable-and-identifiable} ..$ 

```

6.3 New Identity Definitions

Remark 16. *The basic definitions of identity used the type specific quantifiers and identities. We now introduce equivalent alternative definitions that use the general identity and general quantifiers.*

named-theorems *identity-defs*

lemma *identity_E-def*[*identity-defs*]:

basic-identity_E $\equiv \lambda^2 (\lambda x y. (\downarrow O!, x^P) \ \& \ (\downarrow O!, y^P) \ \& \ \Box(\forall F. (\downarrow F, x^P) \equiv (\downarrow F, y^P)))$

unfolding *basic-identity_E-def* *forall- Π_1 -def* **by** *simp*

lemma *identity_E-infix-def*[*identity-defs*]:

$x =_E y \equiv (\downarrow \text{basic-identity}_E, x, y)$ **using** *basic-identity_E-infix-def* .

lemma *identity _{κ} -def*[*identity-defs*]:

op $\equiv \lambda x y. x =_E y \vee (\downarrow A!, x) \ \& \ (\downarrow A!, y) \ \& \ \Box(\forall F. (\downarrow x, F) \equiv (\downarrow y, F))$

unfolding *identity- κ -def* *basic-identity _{κ} -def* *forall- Π_1 -def* **by** *simp*

lemma *identity _{ν} -def*[*identity-defs*]:

op $\equiv \lambda x y. (x^P) =_E (y^P) \vee (\downarrow A!, x^P) \ \& \ (\downarrow A!, y^P) \ \& \ \Box(\forall F. (\downarrow x^P, F) \equiv (\downarrow y^P, F))$

unfolding *identity- ν -def* *identity- κ -def* **by** *simp*

lemma *identity₁-def*[*identity-defs*]:

op $\equiv \lambda F G. \Box(\forall x. (\downarrow x^P, F) \equiv (\downarrow x^P, G))$

unfolding *identity- Π_1 -def* *basic-identity₁-def* *forall- ν -def* **by** *simp*

lemma *identity₂-def*[*identity-defs*]:

op $\equiv \lambda F G. \forall x. (\lambda y. (\downarrow F, x^P, y^P)) = (\lambda y. (\downarrow G, x^P, y^P))$

$\ \& \ (\lambda y. (\downarrow F, y^P, x^P)) = (\lambda y. (\downarrow G, y^P, x^P))$

unfolding *identity- Π_2 -def* *identity- Π_1 -def* *basic-identity₂-def* *forall- ν -def* **by** *simp*

lemma *identity₃-def*[*identity-defs*]:

op $\equiv \lambda F G. \forall x y. (\lambda z. (\downarrow F, z^P, x^P, y^P)) = (\lambda z. (\downarrow G, z^P, x^P, y^P))$

$\ \& \ (\lambda z. (\downarrow F, x^P, z^P, y^P)) = (\lambda z. (\downarrow G, x^P, z^P, y^P))$

$\ \& \ (\lambda z. (\downarrow F, x^P, y^P, z^P)) = (\lambda z. (\downarrow G, x^P, y^P, z^P))$

unfolding *identity- Π_3 -def* *identity- Π_1 -def* *basic-identity₃-def* *forall- ν -def* **by** *simp*

lemma *identity_o-def*[*identity-defs*]: *op* $\equiv \lambda F G. (\lambda y. F) = (\lambda y. G)$

unfolding *identity-o-def* *identity- Π_1 -def* *basic-identity_o-def* **by** *simp*

7 The Axioms of Principia Metaphysica

Remark 17. *The axioms of PM can now be derived from the Semantics and the meta-logic.*

locale *Axioms*

begin

interpretation *MetaSolver* .

interpretation *Semantics* .

named-theorems *axiom*

7.1 Closures

Remark 18. *The special syntax $[[\cdot]]$ is introduced for axioms. This allows to formulate special rules resembling the concepts of closures in PM. To simplify the instantiation of axioms later, special attributes are introduced to automatically resolve the special axiom syntax. Necessitation averse axioms are stated with the syntax for actual validity $[-]$.*

definition *axiom* :: $\text{o} \Rightarrow \text{bool}$ ($[[\cdot]]$) **where** *axiom* $\equiv \lambda \varphi. \forall v. [\varphi \text{ in } v]$

method *axiom-meta-solver* = ((*unfold axiom-def*)?, *rule allI*, *meta-solver*,
(*simp* | (*auto*; *fail*)))?

lemma *axiom-instance*[*axiom*]: $[[\varphi]] \Rightarrow [\varphi \text{ in } v]$

unfolding *axiom-def* **by** *simp*

lemma *closures-universal*[*axiom*]: $(\bigwedge x. [[\varphi x]]) \Rightarrow [[\forall x. \varphi x]]$

by *axiom-meta-solver*

lemma *closures-actualization*[*axiom*]: $[[\varphi]] \Rightarrow [[\mathcal{A} \varphi]]$

by *axiom-meta-solver*

```

lemma closures-necessitation[axiom]:  $[[\varphi]] \implies [[\Box \varphi]]$ 
  by axiom-meta-solver
lemma necessitation-averse-axiom-instance[axiom]:  $[\varphi] \implies [\varphi \text{ in } dw]$ 
  by meta-solver
lemma necessitation-averse-closures-universal[axiom]:  $(\bigwedge x. [\varphi x]) \implies [\forall x. \varphi x]$ 
  by meta-solver

attribute-setup axiom-instance = ⟨⟨
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm axiom-instance}))
  ⟩⟩

attribute-setup necessitation-averse-axiom-instance = ⟨⟨
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm necessitation-averse-axiom-instance}))
  ⟩⟩

attribute-setup axiom-necessitation = ⟨⟨
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm closures-necessitation}))
  ⟩⟩

attribute-setup axiom-actualization = ⟨⟨
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm closures-actualization}))
  ⟩⟩

attribute-setup axiom-universal = ⟨⟨
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm closures-universal}))
  ⟩⟩

```

7.2 Axioms for Negations and Conditionals

```

lemma pl-1[axiom]:
   $[[\varphi \rightarrow (\psi \rightarrow \varphi)]]$ 
  by axiom-meta-solver
lemma pl-2[axiom]:
   $[[((\varphi \rightarrow (\psi \rightarrow \chi)) \rightarrow ((\varphi \rightarrow \psi) \rightarrow (\varphi \rightarrow \chi)))]]$ 
  by axiom-meta-solver
lemma pl-3[axiom]:
   $[[((\neg \varphi \rightarrow \neg \psi) \rightarrow ((\neg \varphi \rightarrow \psi) \rightarrow \varphi)]]$ 
  by axiom-meta-solver

```

7.3 Axioms of Identity

```

lemma l-identity[axiom]:
   $[[\alpha = \beta \rightarrow (\varphi \alpha \rightarrow \varphi \beta)]]$ 
  using l-identity apply cut-tac by axiom-meta-solver

```

7.4 Axioms of Quantification

Remark 19. The axioms of quantification differ slightly from the axioms in *Principia Metaphysica*. The differences can be justified, though.

- Axiom *cqt-2* is omitted, as the embedding does not distinguish between terms and variables. Instead it is combined with *cqt-1*, in which the corresponding condition is omitted, and with *cqt-5* in its modified form *cqt-5-mod*.
- Note that the all quantifier for individuals only ranges over the datatype ν , which is always a denoting term and not a definite description in the embedding.
- The case of definite descriptions is handled separately in axiom *cqt-1- κ* : If a formula on datatype κ holds for all denoting terms ($\forall \alpha. \varphi (\alpha^P)$) then the formula holds for an individual $\varphi \alpha$, if α denotes, i.e. $\exists \beta. (\beta^P) = \alpha$.

- Although axiom *cqt-5* can be stated without modification, it is not a suitable formulation for the embedding. Therefore the seemingly stronger version *cqt-5-mod* is stated as well. On a closer look, though, *cqt-5-mod* immediately follows from the original *cqt-5* together with the omitted *cqt-2*.

```

lemma cqt-1[axiom]:
  [[(∀ α. φ α) → φ α]]
  by axiom-meta-solver
lemma cqt-1-κ[axiom]:
  [[(∀ α. φ (αP)) → ((∃ β . (βP) = α) → φ α)]]
  proof –
  {
    fix v
    assume 1: [(∀ α. φ (αP)) in v]
    assume [(∃ β . (βP) = α) in v]
    then obtain β where 2:
      [(βP) = α in v] by (rule ExERule)
    hence [φ (βP) in v] using 1 Alle by blast
    hence [φ α in v]
      using l-identity[where φ=φ, axiom-instance]
      ImplS 2 by simp
  }
  thus [[(∀ α. φ (αP)) → ((∃ β . (βP) = α) → φ α)]]
    unfolding axiom-def using ImplI by blast
qed
lemma cqt-3[axiom]:
  [[(∀ α. φ α → ψ α) → ((∀ α. φ α) → (∀ α. ψ α))]]
  by axiom-meta-solver
lemma cqt-4[axiom]:
  [[φ → (∀ α. φ)]]
  by axiom-meta-solver

inductive SimpleExOrEnc
  where SimpleExOrEnc (λ x . ⟨F, x⟩)
    | SimpleExOrEnc (λ x . ⟨F, x, y⟩)
    | SimpleExOrEnc (λ x . ⟨F, y, x⟩)
    | SimpleExOrEnc (λ x . ⟨F, x, y, z⟩)
    | SimpleExOrEnc (λ x . ⟨F, y, x, z⟩)
    | SimpleExOrEnc (λ x . ⟨F, y, z, x⟩)
    | SimpleExOrEnc (λ x . ⟨x, F⟩)

lemma cqt-5[axiom]:
  assumes SimpleExOrEnc ψ
  shows [[(ψ (ι x . φ x)) → (∃ α. (αP) = (ι x . φ x))]]
  proof –
    have ∀ w . [(ψ (ι x . φ x)) in w] → (∃ o1 . Some o1 = dκ (ι x . φ x))
      using assms apply induct by (meta-solver;metis)+
    moreover hence
      ∀ w . [(ψ (ι x . φ x)) in w] → (that φ) = (denotation (that φ))P
      apply transfer by (metis (mono-tags, lifting) eq-snd-iff fst-conv option.simps(3))
    ultimately show ?thesis
      apply cut-tac unfolding identity-κ-def
      apply axiom-meta-solver by metis
qed

lemma cqt-5-mod[axiom]:
  assumes SimpleExOrEnc ψ
  shows [[ψ x → (∃ α . (αP) = x)]
  proof –
    have ∀ w . [(ψ x) in w] → (∃ o1 . Some o1 = dκ x)
      using assms apply induct by (meta-solver;metis)+
    moreover hence ∀ w . [(ψ x) in w] → (x) = (denotation (x))P
      apply transfer by (metis (mono-tags, lifting) eq-snd-iff fst-conv option.simps(3))

```

```

ultimately show ?thesis
  apply cut-tac unfolding identity-κ-def
  apply axiom-meta-solver by metis
qed

```

7.5 Axioms of Actuality

Remark 20. *The necessitation averse axiom of actuality is stated to be actually true; for the statement as a proper axiom (for which necessitation would be allowed) nitpick can find a counter-model as desired.*

```

lemma logic-actual[axiom]: [( $\mathcal{A}\varphi \equiv \varphi$ )]
  apply meta-solver by auto
lemma [[( $\mathcal{A}\varphi \equiv \varphi$ )]
  nitpick[user-axioms, expect = genuine, card = 1, card i = 2]
oops — Counter-model by nitpick

lemma logic-actual-nec-1[axiom]:
  [[( $\mathcal{A}\neg\varphi \equiv \neg\mathcal{A}\varphi$ )]
  by axiom-meta-solver
lemma logic-actual-nec-2[axiom]:
  [[( $\mathcal{A}(\varphi \rightarrow \psi) \equiv (\mathcal{A}\varphi \rightarrow \mathcal{A}\psi)$ )]
  by axiom-meta-solver
lemma logic-actual-nec-3[axiom]:
  [[( $\mathcal{A}(\forall\alpha. \varphi \alpha) \equiv (\forall\alpha. \mathcal{A}(\varphi \alpha))$ )]
  by axiom-meta-solver
lemma logic-actual-nec-4[axiom]:
  [[( $\mathcal{A}\varphi \equiv \mathcal{A}\mathcal{A}\varphi$ )]
  by axiom-meta-solver

```

7.6 Axioms of Necessity

```

lemma qml-1[axiom]:
  [[( $\Box(\varphi \rightarrow \psi) \rightarrow (\Box\varphi \rightarrow \Box\psi)$ )]
  by axiom-meta-solver
lemma qml-2[axiom]:
  [[( $\Box\varphi \rightarrow \varphi$ )]
  by axiom-meta-solver
lemma qml-3[axiom]:
  [[( $\Diamond\varphi \rightarrow \Box\Diamond\varphi$ )]
  by axiom-meta-solver
lemma qml-4[axiom]:
  [[( $\Diamond(\exists x. (\Box!x^P) \ \& \ \Diamond\neg(\Box!x^P)) \ \& \ \Diamond\neg(\exists x. (\Box!x^P) \ \& \ \Diamond\neg(\Box!x^P))$ )]
  unfolding axiom-def
  using PossiblyContingentObjectExistsAxiom
  PossiblyNoContingentObjectExistsAxiom
  apply (simp add: meta-defs meta-aux conn-defs forall-ν-def
    split: ν.split v.split)
  by (metis νν-ων-is-ων v.distinct(1) v.inject(1))

```

7.7 Axioms of Necessity and Actuality

```

lemma qml-act-1[axiom]:
  [[( $\mathcal{A}\varphi \rightarrow \Box\mathcal{A}\varphi$ )]
  by axiom-meta-solver
lemma qml-act-2[axiom]:
  [[( $\Box\varphi \equiv \mathcal{A}(\Box\varphi)$ )]
  by axiom-meta-solver

```

7.8 Axioms of Descriptions

```

lemma descriptions[axiom]:
  [[( $x^P = (\iota x. \varphi x) \equiv (\forall z. (\mathcal{A}(\varphi z) \equiv z = x))$ )]

```

```

unfolding axiom-def
proof (rule allI, rule EquivI; rule)
  fix v
  assume [ $x^P = (\iota x. \varphi x)$  in v]
  moreover hence 1:
     $\exists o_1 o_2. \text{Some } o_1 = d_\kappa (x^P) \wedge \text{Some } o_2 = d_\kappa (\iota x. \varphi x) \wedge o_1 = o_2$ 
    apply cut-tac unfolding identity- $\kappa$ -def by meta-solver
  then obtain  $o_1 o_2$  where 2:
     $\text{Some } o_1 = d_\kappa (x^P) \wedge \text{Some } o_2 = d_\kappa (\iota x. \varphi x) \wedge o_1 = o_2$ 
    by auto
  hence 3:
     $(\exists x. ((w_0 \models \varphi x) \wedge (\forall y. (w_0 \models \varphi y) \longrightarrow y = x)))$ 
     $\wedge d_\kappa (\iota x. \varphi x) = \text{Some } (THE x. (w_0 \models \varphi x))$ 
    using D3 by (metis option.distinct(1))
  then obtain X where 4:
     $((w_0 \models \varphi X) \wedge (\forall y. (w_0 \models \varphi y) \longrightarrow y = X))$ 
    by auto
  moreover have  $o_1 = (THE x. (w_0 \models \varphi x))$ 
    using 2 3 by auto
  ultimately have 5:  $X = o_1$ 
    by (metis (mono-tags) theI)
  have  $\forall z. [\mathcal{A}\varphi z \text{ in } v] = [(z^P) = (x^P) \text{ in } v]$ 
  proof
    fix z
    have  $[\mathcal{A}\varphi z \text{ in } v] \Longrightarrow [(z^P) = (x^P) \text{ in } v]$ 
      unfolding identity- $\kappa$ -def apply meta-solver
      unfolding d $\kappa$ -def using 4 5 2 apply transfer
      apply simp by (metis w0-def)
    moreover have  $[(z^P) = (x^P) \text{ in } v] \Longrightarrow [\mathcal{A}\varphi z \text{ in } v]$ 
      unfolding identity- $\kappa$ -def apply meta-solver
      using 2 4 5 apply transfer apply simp
      by (metis w0-def)
    ultimately show  $[\mathcal{A}\varphi z \text{ in } v] = [(z^P) = (x^P) \text{ in } v]$ 
      by auto
  qed
  thus  $[\forall z. \mathcal{A}\varphi z \equiv (z) = (x) \text{ in } v]$ 
    unfolding identity- $\nu$ -def
    by (simp add: AllI EquivS)
next
  fix v
  assume  $[\forall z. \mathcal{A}\varphi z \equiv (z) = (x) \text{ in } v]$ 
  hence  $\bigwedge z. (dw \models \varphi z) = (\exists o_1 o_2. \text{Some } o_1 = d_\kappa (z^P) \wedge \text{Some } o_2 = d_\kappa (x^P) \wedge o_1 = o_2)$ 
    apply cut-tac unfolding identity- $\nu$ -def identity- $\kappa$ -def by meta-solver
  hence  $\forall z. \text{evalo } (\varphi z) \text{ dj } dw = (z = x)$  apply transfer by simp
  moreover hence  $\exists! x. \text{evalo } (\varphi x) \text{ dj } dw$  by metis
  ultimately have  $x^P = (\iota x. \varphi x)$  unfolding TheS by (simp add:  $\nu\kappa$ -def)
  thus  $[x^P = (\iota x. \varphi x) \text{ in } v]$ 
    using Eq $\kappa$ S unfolding identity- $\kappa$ -def by (metis d $\kappa$ -proper)
  qed

```

7.9 Axioms for Complex Relation Terms

lemma *lambda-predicates-1* [*axiom*]:

$(\lambda x. \varphi x) = (\lambda y. \varphi y) ..$

lemma *lambda-predicates-2-1* [*axiom*]:

assumes *IsPropositionalInX* φ

shows $[(\lambda x. \varphi (x^P), x^P) \equiv \varphi (x^P)]$

apply *axiom-meta-solver*

using *D5-1* [*OF assms*]

apply *transfer* **by** *simp*

lemma *lambda-predicates-2-2*[*axiom*]:
assumes *IsPropositionalInXYZ* φ
shows $[[\langle (\lambda^2 (\lambda x y . \varphi (x^P) (y^P))) , x^P, y^P \rangle \equiv \varphi (x^P) (y^P)]]$
apply *axiom-meta-solver*
using *D5-2[OF assms]* **apply** *transfer* **by** *simp*

lemma *lambda-predicates-2-3*[*axiom*]:
assumes *IsPropositionalInXYZ* φ
shows $[[\langle (\lambda^3 (\lambda x y z . \varphi (x^P) (y^P) (z^P))) , x^P, y^P, z^P \rangle \equiv \varphi (x^P) (y^P) (z^P)]]$
proof –
have $\square[\langle (\lambda^3 (\lambda x y z . \varphi (x^P) (y^P) (z^P))) , x^P, y^P, z^P \rangle \rightarrow \varphi (x^P) (y^P) (z^P)]$
apply *meta-solver* **using** *D5-3[OF assms]* **by** *auto*
moreover have
 $\square[\varphi (x^P) (y^P) (z^P) \rightarrow \langle (\lambda^3 (\lambda x y z . \varphi (x^P) (y^P) (z^P))) , x^P, y^P, z^P \rangle]$
apply *axiom-meta-solver*
using *D5-3[OF assms]* **unfolding** *d3-def ex3-def*
apply *transfer* **apply** *simp* **by** *fastforce*
ultimately show *?thesis* **unfolding** *axiom-def equiv-def ConjS* **by** *blast*
qed

lemma *lambda-predicates-3-0*[*axiom*]:
 $[[\langle \lambda^0 \varphi \rangle = \varphi]]$
unfolding *identity-defs*
apply *axiom-meta-solver*
by (*simp add: meta-defs meta-aux*)

lemma *lambda-predicates-3-1*[*axiom*]:
 $[[\langle \lambda x . \langle F, x^P \rangle \rangle = F]]$
unfolding *identity-defs*
apply *axiom-meta-solver*
by (*simp add: meta-defs meta-aux*)

lemma *lambda-predicates-3-2*[*axiom*]:
 $[[\langle \lambda^2 (\lambda x y . \langle F, x^P, y^P \rangle) \rangle = F]]$
unfolding *identity-defs*
apply *axiom-meta-solver*
by (*simp add: meta-defs meta-aux*)

lemma *lambda-predicates-3-3*[*axiom*]:
 $[[\langle \lambda^3 (\lambda x y z . \langle F, x^P, y^P, z^P \rangle) \rangle = F]]$
unfolding *identity-defs*
apply *axiom-meta-solver*
by (*simp add: meta-defs meta-aux*)

lemma *lambda-predicates-4-0*[*axiom*]:
assumes $\bigwedge x. [\langle \mathcal{A}(\varphi x \equiv \psi x) \rangle \text{ in } v]$
shows $[[\langle \lambda^0 (\chi (\iota x. \varphi x)) \rangle = \lambda^0 (\chi (\iota x. \psi x)) \text{ in } v]]$
unfolding *identity-defs* **using** *assms* **apply** *cut-tac*
apply *meta-solver* **by** (*auto simp: meta-defs*)

lemma *lambda-predicates-4-1*[*axiom*]:
assumes $\bigwedge x. [\langle \mathcal{A}(\varphi x \equiv \psi x) \rangle \text{ in } v]$
shows $[[\langle \lambda x . \chi (\iota x. \varphi x) x \rangle = \langle \lambda x . \chi (\iota x. \psi x) x \rangle \text{ in } v]]$
unfolding *identity-defs* **using** *assms* **apply** *cut-tac*
apply *meta-solver* **by** (*auto simp: meta-defs*)

lemma *lambda-predicates-4-2*[*axiom*]:
assumes $\bigwedge x. [\langle \mathcal{A}(\varphi x \equiv \psi x) \rangle \text{ in } v]$
shows $[[\langle \lambda^2 (\lambda x y . \chi (\iota x. \varphi x) x y) \rangle = \langle \lambda^2 (\lambda x y . \chi (\iota x. \psi x) x y) \rangle \text{ in } v]]$
unfolding *identity-defs* **using** *assms* **apply** *cut-tac*
apply *meta-solver* **by** (*auto simp: meta-defs*)

lemma *lambda-predicates-4-3*[*axiom*]:

```

assumes  $\bigwedge x. [(\mathcal{A}(\varphi \ x \equiv \psi \ x)) \text{ in } v]$ 
shows  $[(\lambda^3 (\lambda \ x \ y \ z . \chi (\iota x. \varphi \ x) \ x \ y \ z)) = (\lambda^3 (\lambda \ x \ y \ z . \chi (\iota x. \psi \ x) \ x \ y \ z)) \text{ in } v]$ 
unfolding identity-defs using assms apply cut-tac
apply meta-solver by (auto simp: meta-defs)

```

7.10 Axioms of Encoding

```

lemma encoding[axiom]:
   $[[\langle x, F \rangle \rightarrow \Box \langle x, F \rangle]]$ 
  by axiom-meta-solver
lemma nocoder[axiom]:
   $[[\langle O!, x \rangle \rightarrow \neg(\exists F . \langle x, F \rangle)]]$ 
  unfolding axiom-def
  apply (rule allI, rule ImplI, subst (asm) OrdS)
  apply meta-solver unfolding en-def
  by (metis v.simps(5) mem-Collect-eq option.sel)
lemma A-objects[axiom]:
   $[[\exists x. \langle A!, x^P \rangle \ \& \ (\forall F . (\langle x^P, F \rangle \equiv \varphi \ F))]]$ 
  unfolding axiom-def
  proof (rule allI, rule ExIRule)
    fix v
    let ?x =  $\alpha v \ \{ F . [\varphi \ F \text{ in } v] \}$ 
    have  $[\langle A!, ?x^P \rangle \text{ in } v]$  by (simp add: AbsS d $_{\kappa}$ -proper)
    moreover have  $[(\forall F. \langle ?x^P, F \rangle \equiv \varphi \ F) \text{ in } v]$ 
      apply meta-solver unfolding en-def
      using d $_1$ .rep-eq d $_{\kappa}$ -def d $_{\kappa}$ -proper eval $\Pi_1$ -inverse by auto
    ultimately show  $[\langle A!, ?x^P \rangle \ \& \ (\forall F. \langle ?x^P, F \rangle \equiv \varphi \ F) \text{ in } v]$ 
      by (simp only: ConjS)
  qed
end

```

8 Definitions

Various definitions needed throughout PLM.

8.1 Property Negations

```

consts propnot :: 'a  $\Rightarrow$  'a ( $-$  [90] 90)
overloading propnot $_0 \equiv$  propnot ::  $\Pi_0 \Rightarrow \Pi_0$ 
  propnot $_1 \equiv$  propnot ::  $\Pi_1 \Rightarrow \Pi_1$ 
  propnot $_2 \equiv$  propnot ::  $\Pi_2 \Rightarrow \Pi_2$ 
  propnot $_3 \equiv$  propnot ::  $\Pi_3 \Rightarrow \Pi_3$ 
begin
  definition propnot $_0$  ::  $\Pi_0 \Rightarrow \Pi_0$  where
    propnot $_0 \equiv \lambda p . \lambda^0 (\neg p)$ 
  definition propnot $_1$  where
    propnot $_1 \equiv \lambda F . \lambda x . \neg \langle F, x^P \rangle$ 
  definition propnot $_2$  where
    propnot $_2 \equiv \lambda F . \lambda^2 (\lambda x \ y . \neg \langle F, x^P, y^P \rangle)$ 
  definition propnot $_3$  where
    propnot $_3 \equiv \lambda F . \lambda^3 (\lambda x \ y \ z . \neg \langle F, x^P, y^P, z^P \rangle)$ 
end

```

```

named-theorems propnot-defs
declare propnot $_0$ -def[propnot-defs] propnot $_1$ -def[propnot-defs]
  propnot $_2$ -def[propnot-defs] propnot $_3$ -def[propnot-defs]

```

8.2 Noncontingent and Contingent Relations

```

consts Necessary :: 'a  $\Rightarrow$  o
overloading Necessary $_0 \equiv$  Necessary ::  $\Pi_0 \Rightarrow o$ 

```


$Necessary_1 \equiv Necessary :: \Pi_1 \Rightarrow o$
 $Necessary_2 \equiv Necessary :: \Pi_2 \Rightarrow o$
 $Necessary_3 \equiv Necessary :: \Pi_3 \Rightarrow o$

begin

definition $Necessary_0$ **where**
 $Necessary_0 \equiv \lambda p . \Box p$

definition $Necessary_1 :: \Pi_1 \Rightarrow o$ **where**
 $Necessary_1 \equiv \lambda F . \Box(\forall x . \langle F, x^P \rangle)$

definition $Necessary_2$ **where**
 $Necessary_2 \equiv \lambda F . \Box(\forall x y . \langle F, x^P, y^P \rangle)$

definition $Necessary_3$ **where**
 $Necessary_3 \equiv \lambda F . \Box(\forall x y z . \langle F, x^P, y^P, z^P \rangle)$

end

named-theorems $Necessary-defs$

declare $Necessary_0-def[Necessary-defs]$ $Necessary_1-def[Necessary-defs]$
 $Necessary_2-def[Necessary-defs]$ $Necessary_3-def[Necessary-defs]$

consts $Impossible :: 'a \Rightarrow o$

overloading $Impossible_0 \equiv Impossible :: \Pi_0 \Rightarrow o$
 $Impossible_1 \equiv Impossible :: \Pi_1 \Rightarrow o$
 $Impossible_2 \equiv Impossible :: \Pi_2 \Rightarrow o$
 $Impossible_3 \equiv Impossible :: \Pi_3 \Rightarrow o$

begin

definition $Impossible_0$ **where**
 $Impossible_0 \equiv \lambda p . \Box \neg p$

definition $Impossible_1$ **where**
 $Impossible_1 \equiv \lambda F . \Box(\forall x . \neg \langle F, x^P \rangle)$

definition $Impossible_2$ **where**
 $Impossible_2 \equiv \lambda F . \Box(\forall x y . \neg \langle F, x^P, y^P \rangle)$

definition $Impossible_3$ **where**
 $Impossible_3 \equiv \lambda F . \Box(\forall x y z . \neg \langle F, x^P, y^P, z^P \rangle)$

end

named-theorems $Impossible-defs$

declare $Impossible_0-def[Impossible-defs]$ $Impossible_1-def[Impossible-defs]$
 $Impossible_2-def[Impossible-defs]$ $Impossible_3-def[Impossible-defs]$

definition $NonContingent$ **where**
 $NonContingent \equiv \lambda F . (Necessary F) \vee (Impossible F)$

definition $Contingent$ **where**
 $Contingent \equiv \lambda F . \neg(Necessary F \vee Impossible F)$

definition $ContingentlyTrue :: o \Rightarrow o$ **where**
 $ContingentlyTrue \equiv \lambda p . p \ \& \ \Diamond \neg p$

definition $ContingentlyFalse :: o \Rightarrow o$ **where**
 $ContingentlyFalse \equiv \lambda p . \neg p \ \& \ \Diamond p$

definition $WeaklyContingent$ **where**
 $WeaklyContingent \equiv \lambda F . Contingent F \ \& \ (\forall x . \Diamond \langle F, x^P \rangle \rightarrow \Box \langle F, x^P \rangle)$

8.3 Null and Universal Objects

definition $Null :: \kappa \Rightarrow o$ **where**
 $Null \equiv \lambda x . \langle A!, x \rangle \ \& \ \neg(\exists F . \langle x, F \rangle)$

definition $Universal :: \kappa \Rightarrow o$ **where**
 $Universal \equiv \lambda x . \langle A!, x \rangle \ \& \ (\forall F . \langle x, F \rangle)$

definition $NullObject :: \kappa (a_0)$ **where**
 $NullObject \equiv (\iota x . Null (x^P))$

definition $UniversalObject :: \kappa (a_V)$ **where**
 $UniversalObject \equiv (\iota x . Universal (x^P))$

8.4 Propositional Properties

definition *Propositional* **where**

Propositional $F \equiv \exists p . F = (\lambda x . p)$

8.5 Indiscriminate Properties

definition *Indiscriminate* $:: \Pi_1 \Rightarrow 0$ **where**

Indiscriminate $\equiv \lambda F . \Box((\exists x . \langle F, x^P \rangle) \rightarrow (\forall x . \langle F, x^P \rangle))$

8.6 Miscellaneous

definition *not-identical_E* $:: \kappa \Rightarrow \kappa \Rightarrow 0$ (**infixl** \neq_E 63)

where *not-identical_E* $\equiv \lambda x y . \langle (\lambda^2 (\lambda x y . x^P =_E y^P))^- , x, y \rangle$

9 The Deductive System PLM

declare *meta-defs*[no-atp] *meta-aux*[no-atp]

locale *PLM* = *Axioms*

begin

9.1 Automatic Solver

named-theorems *PLM*

named-theorems *PLM-intro*

named-theorems *PLM-elim*

named-theorems *PLM-dest*

named-theorems *PLM-subst*

method *PLM-solver* **declares** *PLM-intro* *PLM-elim* *PLM-subst* *PLM-dest* *PLM*

= ((*assumption* | (*match axiom* **in** *A*: $\llbracket \varphi \rrbracket$ **for** $\varphi \Rightarrow \langle \text{fact } A[\text{axiom-instance}] \rangle$)
| *fact* *PLM* | *rule* *PLM-intro* | *subst* *PLM-subst* | *subst* (*asm*) *PLM-subst*
| *fastforce* | *safe* | *drule* *PLM-dest* | *erule* *PLM-elim*); (*PLM-solver*)?)

9.2 Modus Ponens

lemma *modus-ponens*[*PLM*]:

$\llbracket \varphi \text{ in } v \rrbracket; [\varphi \rightarrow \psi \text{ in } v] \Longrightarrow [\psi \text{ in } v]$

by (*simp add: Semantics.T5*)

9.3 Axioms

interpretation *Axioms* .

declare *axiom*[*PLM*]

9.4 (Modally Strict) Proofs and Derivations

lemma *vdash-properties-6*[no-atp]:

$\llbracket \varphi \text{ in } v \rrbracket; [\varphi \rightarrow \psi \text{ in } v] \Longrightarrow [\psi \text{ in } v]$

using *modus-ponens* .

lemma *vdash-properties-9*[*PLM*]:

$[\varphi \text{ in } v] \Longrightarrow [\psi \rightarrow \varphi \text{ in } v]$

using *modus-ponens* *pl-1 axiom-instance* **by** *blast*

lemma *vdash-properties-10*[*PLM*]:

$[\varphi \rightarrow \psi \text{ in } v] \Longrightarrow ([\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v])$

using *vdash-properties-6* .

attribute-setup *deduction* = $\langle\langle$

Scan.succeed (*Thm.rule-attribute* \Box

(*fn* - => *fn thm* => *thm RS* @{*thm vdash-properties-10*}))

$\rangle\rangle$

9.5 GEN and RN

lemma *rule-gen*[PLM]:

$\llbracket \bigwedge \alpha . [\varphi \alpha \text{ in } v] \rrbracket \Longrightarrow [\forall \alpha . \varphi \alpha \text{ in } v]$
by (*simp add: Semantics.T8*)

lemma *RN-2*[PLM]:

$(\bigwedge v . [\psi \text{ in } v] \Longrightarrow [\varphi \text{ in } v]) \Longrightarrow ([\Box \psi \text{ in } v] \Longrightarrow [\Box \varphi \text{ in } v])$
by (*simp add: Semantics.T6*)

lemma *RN*[PLM]:

$(\bigwedge v . [\varphi \text{ in } v]) \Longrightarrow [\Box \varphi \text{ in } v]$
using *gml-3*[*axiom-necessitation, axiom-instance*] *RN-2* **by** *blast*

9.6 Negations and Conditionals

lemma *if-p-then-p*[PLM]:

$[\varphi \rightarrow \varphi \text{ in } v]$
using *pl-1 pl-2 vdash-properties-10 axiom-instance* **by** *blast*

lemma *deduction-theorem*[PLM, PLM-intro]:

$\llbracket [\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v] \rrbracket \Longrightarrow [\varphi \rightarrow \psi \text{ in } v]$
by (*simp add: Semantics.T5*)

lemmas *CP = deduction-theorem*

lemma *ded-thm-cor-3*[PLM]:

$\llbracket [\varphi \rightarrow \psi \text{ in } v]; [\psi \rightarrow \chi \text{ in } v] \rrbracket \Longrightarrow [\varphi \rightarrow \chi \text{ in } v]$
by (*meson pl-2 vdash-properties-10 vdash-properties-9 axiom-instance*)

lemma *ded-thm-cor-4*[PLM]:

$\llbracket [\varphi \rightarrow (\psi \rightarrow \chi) \text{ in } v]; [\psi \text{ in } v] \rrbracket \Longrightarrow [\varphi \rightarrow \chi \text{ in } v]$
by (*meson pl-2 vdash-properties-10 vdash-properties-9 axiom-instance*)

lemma *useful-tautologies-1*[PLM]:

$[\neg \neg \varphi \rightarrow \varphi \text{ in } v]$
by (*meson pl-1 pl-3 ded-thm-cor-3 ded-thm-cor-4 axiom-instance*)

lemma *useful-tautologies-2*[PLM]:

$[\varphi \rightarrow \neg \neg \varphi \text{ in } v]$
by (*meson pl-1 pl-3 ded-thm-cor-3 useful-tautologies-1 vdash-properties-10 axiom-instance*)

lemma *useful-tautologies-3*[PLM]:

$[\neg \varphi \rightarrow (\varphi \rightarrow \psi) \text{ in } v]$
by (*meson pl-1 pl-2 pl-3 ded-thm-cor-3 ded-thm-cor-4 axiom-instance*)

lemma *useful-tautologies-4*[PLM]:

$[(\neg \psi \rightarrow \neg \varphi) \rightarrow (\varphi \rightarrow \psi) \text{ in } v]$
by (*meson pl-1 pl-2 pl-3 ded-thm-cor-3 ded-thm-cor-4 axiom-instance*)

lemma *useful-tautologies-5*[PLM]:

$[(\varphi \rightarrow \psi) \rightarrow (\neg \psi \rightarrow \neg \varphi) \text{ in } v]$
by (*metis CP useful-tautologies-4 vdash-properties-10*)

lemma *useful-tautologies-6*[PLM]:

$[(\varphi \rightarrow \neg \psi) \rightarrow (\psi \rightarrow \neg \varphi) \text{ in } v]$
by (*metis CP useful-tautologies-4 vdash-properties-10*)

lemma *useful-tautologies-7*[PLM]:

$[(\neg \varphi \rightarrow \psi) \rightarrow (\neg \psi \rightarrow \varphi) \text{ in } v]$
using *ded-thm-cor-3 useful-tautologies-4 useful-tautologies-5 useful-tautologies-6* **by** *blast*

lemma *useful-tautologies-8*[PLM]:

$[\varphi \rightarrow (\neg \psi \rightarrow \neg(\varphi \rightarrow \psi)) \text{ in } v]$
by (*meson ded-thm-cor-3 CP useful-tautologies-5*)

lemma *useful-tautologies-9*[PLM]:

$[(\varphi \rightarrow \psi) \rightarrow ((\neg \varphi \rightarrow \psi) \rightarrow \psi) \text{ in } v]$
by (*metis CP useful-tautologies-4 vdash-properties-10*)

lemma *useful-tautologies-10*[PLM]:

$[(\varphi \rightarrow \neg \psi) \rightarrow ((\varphi \rightarrow \psi) \rightarrow \neg \varphi) \text{ in } v]$
by (*metis ded-thm-cor-3 CP useful-tautologies-6*)

lemma *modus-tollens-1*[PLM]:

$$[[\varphi \rightarrow \psi \text{ in } v]; [\neg\psi \text{ in } v]] \Longrightarrow [\neg\varphi \text{ in } v]$$
by (*metis ded-thm-cor-3 ded-thm-cor-4 useful-tautologies-3 useful-tautologies-7 vdash-properties-10*)

lemma *modus-tollens-2*[PLM]:

$$[[\varphi \rightarrow \neg\psi \text{ in } v]; [\psi \text{ in } v]] \Longrightarrow [\neg\varphi \text{ in } v]$$
using *modus-tollens-1 useful-tautologies-2 vdash-properties-10* **by** *blast*

lemma *contraposition-1*[PLM]:

$$[\varphi \rightarrow \psi \text{ in } v] = [\neg\psi \rightarrow \neg\varphi \text{ in } v]$$
using *useful-tautologies-4 useful-tautologies-5 vdash-properties-10* **by** *blast*

lemma *contraposition-2*[PLM]:

$$[\varphi \rightarrow \neg\psi \text{ in } v] = [\psi \rightarrow \neg\varphi \text{ in } v]$$
using *contraposition-1 ded-thm-cor-3 useful-tautologies-1* **by** *blast*

lemma *reductio-aa-1*[PLM]:

$$[[\neg\varphi \text{ in } v] \Longrightarrow [\neg\psi \text{ in } v]; [\neg\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v]] \Longrightarrow [\varphi \text{ in } v]$$
using *CP modus-tollens-2 useful-tautologies-1 vdash-properties-10* **by** *blast*

lemma *reductio-aa-2*[PLM]:

$$[[\varphi \text{ in } v] \Longrightarrow [\neg\psi \text{ in } v]; [\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v]] \Longrightarrow [\neg\varphi \text{ in } v]$$
by (*meson contraposition-1 reductio-aa-1*)

lemma *reductio-aa-3*[PLM]:

$$[[\neg\varphi \rightarrow \neg\psi \text{ in } v]; [\neg\varphi \rightarrow \psi \text{ in } v]] \Longrightarrow [\varphi \text{ in } v]$$
using *reductio-aa-1 vdash-properties-10* **by** *blast*

lemma *reductio-aa-4*[PLM]:

$$[[\varphi \rightarrow \neg\psi \text{ in } v]; [\varphi \rightarrow \psi \text{ in } v]] \Longrightarrow [\neg\varphi \text{ in } v]$$
using *reductio-aa-2 vdash-properties-10* **by** *blast*

lemma *raa-cor-1*[PLM]:

$$[[\varphi \text{ in } v]; [\neg\psi \text{ in } v] \Longrightarrow [\neg\varphi \text{ in } v]] \Longrightarrow ([\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v])$$
using *reductio-aa-1 vdash-properties-9* **by** *blast*

lemma *raa-cor-2*[PLM]:

$$[[\neg\varphi \text{ in } v]; [\neg\psi \text{ in } v] \Longrightarrow [\varphi \text{ in } v]] \Longrightarrow ([\neg\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v])$$
using *reductio-aa-1 vdash-properties-9* **by** *blast*

lemma *raa-cor-3*[PLM]:

$$[[\varphi \text{ in } v]; [\neg\psi \rightarrow \neg\varphi \text{ in } v]] \Longrightarrow ([\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v])$$
using *raa-cor-1 vdash-properties-10* **by** *blast*

lemma *raa-cor-4*[PLM]:

$$[[\neg\varphi \text{ in } v]; [\neg\psi \rightarrow \varphi \text{ in } v]] \Longrightarrow ([\neg\varphi \text{ in } v] \Longrightarrow [\psi \text{ in } v])$$
using *raa-cor-2 vdash-properties-10* **by** *blast*

Remark 21. *The classical introduction and elimination rules are proven earlier than in PM. The statements proven so far are sufficient for the proofs and using these rules Isabelle can prove the tautologies automatically.*

lemma *intro-elim-1*[PLM]:

$$[[\varphi \text{ in } v]; [\psi \text{ in } v]] \Longrightarrow [\varphi \ \& \ \psi \text{ in } v]$$
unfolding *conj-def* **using** *ded-thm-cor-4 if-p-then-p modus-tollens-2* **by** *blast*

lemmas *&I* = *intro-elim-1*

lemma *intro-elim-2-a*[PLM]:

$$[\varphi \ \& \ \psi \text{ in } v] \Longrightarrow [\varphi \text{ in } v]$$
unfolding *conj-def* **using** *CP reductio-aa-1* **by** *blast*

lemma *intro-elim-2-b*[PLM]:

$$[\varphi \ \& \ \psi \text{ in } v] \Longrightarrow [\psi \text{ in } v]$$
unfolding *conj-def* **using** *pl-1 CP reductio-aa-1 axiom-instance* **by** *blast*

lemmas *&E* = *intro-elim-2-a intro-elim-2-b*

lemma *intro-elim-3-a*[PLM]:

$$[\varphi \text{ in } v] \Longrightarrow [\varphi \vee \psi \text{ in } v]$$
unfolding *disj-def* **using** *ded-thm-cor-4 useful-tautologies-3* **by** *blast*

lemma *intro-elim-3-b*[PLM]:
 $[\psi \text{ in } v] \implies [\varphi \vee \psi \text{ in } v]$
by (*simp only: disj-def vdash-properties-9*)
lemmas $\vee I = \text{intro-elim-3-a intro-elim-3-b}$
lemma *intro-elim-4-a*[PLM]:
 $[[\varphi \vee \psi \text{ in } v]; [\varphi \rightarrow \chi \text{ in } v]; [\psi \rightarrow \chi \text{ in } v]] \implies [\chi \text{ in } v]$
unfolding *disj-def* **by** (*meson reductio-aa-2 vdash-properties-10*)
lemma *intro-elim-4-b*[PLM]:
 $[[\varphi \vee \psi \text{ in } v]; [\neg \varphi \text{ in } v]] \implies [\psi \text{ in } v]$
unfolding *disj-def* **using** *vdash-properties-10* **by** *blast*
lemma *intro-elim-4-c*[PLM]:
 $[[\varphi \vee \psi \text{ in } v]; [\neg \psi \text{ in } v]] \implies [\varphi \text{ in } v]$
unfolding *disj-def* **using** *raa-cor-2 vdash-properties-10* **by** *blast*
lemma *intro-elim-4-d*[PLM]:
 $[[\varphi \vee \psi \text{ in } v]; [\varphi \rightarrow \chi \text{ in } v]; [\psi \rightarrow \Theta \text{ in } v]] \implies [\chi \vee \Theta \text{ in } v]$
unfolding *disj-def* **using** *contraposition-1 ded-thm-cor-3* **by** *blast*
lemma *intro-elim-4-e*[PLM]:
 $[[\varphi \vee \psi \text{ in } v]; [\varphi \equiv \chi \text{ in } v]; [\psi \equiv \Theta \text{ in } v]] \implies [\chi \vee \Theta \text{ in } v]$
unfolding *equiv-def* **using** $\&E(1)$ *intro-elim-4-d* **by** *blast*
lemmas $\vee E = \text{intro-elim-4-a intro-elim-4-b intro-elim-4-c intro-elim-4-d}$
lemma *intro-elim-5*[PLM]:
 $[[\varphi \rightarrow \psi \text{ in } v]; [\psi \rightarrow \varphi \text{ in } v]] \implies [\varphi \equiv \psi \text{ in } v]$
by (*simp only: equiv-def &I*)
lemmas $\equiv I = \text{intro-elim-5}$
lemma *intro-elim-6-a*[PLM]:
 $[[\varphi \equiv \psi \text{ in } v]; [\varphi \text{ in } v]] \implies [\psi \text{ in } v]$
unfolding *equiv-def* **using** $\&E(1)$ *vdash-properties-10* **by** *blast*
lemma *intro-elim-6-b*[PLM]:
 $[[\varphi \equiv \psi \text{ in } v]; [\psi \text{ in } v]] \implies [\varphi \text{ in } v]$
unfolding *equiv-def* **using** $\&E(2)$ *vdash-properties-10* **by** *blast*
lemma *intro-elim-6-c*[PLM]:
 $[[\varphi \equiv \psi \text{ in } v]; [\neg \varphi \text{ in } v]] \implies [\neg \psi \text{ in } v]$
unfolding *equiv-def* **using** $\&E(2)$ *modus-tollens-1* **by** *blast*
lemma *intro-elim-6-d*[PLM]:
 $[[\varphi \equiv \psi \text{ in } v]; [\neg \psi \text{ in } v]] \implies [\neg \varphi \text{ in } v]$
unfolding *equiv-def* **using** $\&E(1)$ *modus-tollens-1* **by** *blast*
lemma *intro-elim-6-e*[PLM]:
 $[[\varphi \equiv \psi \text{ in } v]; [\psi \equiv \chi \text{ in } v]] \implies [\varphi \equiv \chi \text{ in } v]$
by (*metis equiv-def ded-thm-cor-3 &E ≡I*)
lemma *intro-elim-6-f*[PLM]:
 $[[\varphi \equiv \psi \text{ in } v]; [\varphi \equiv \chi \text{ in } v]] \implies [\chi \equiv \psi \text{ in } v]$
by (*metis equiv-def ded-thm-cor-3 &E ≡I*)
lemmas $\equiv E = \text{intro-elim-6-a intro-elim-6-b intro-elim-6-c}$
 $\text{intro-elim-6-d intro-elim-6-e intro-elim-6-f}$
lemma *intro-elim-7*[PLM]:
 $[\varphi \text{ in } v] \implies [\neg \neg \varphi \text{ in } v]$
using *if-p-then-p modus-tollens-2* **by** *blast*
lemmas $\neg \neg I = \text{intro-elim-7}$
lemma *intro-elim-8*[PLM]:
 $[\neg \neg \varphi \text{ in } v] \implies [\varphi \text{ in } v]$
using *if-p-then-p raa-cor-2* **by** *blast*
lemmas $\neg \neg E = \text{intro-elim-8}$

context

begin

private lemma *NotNotI*[PLM-intro]:

$[\varphi \text{ in } v] \implies [\neg(\neg \varphi) \text{ in } v]$

by (*simp add: $\neg \neg I$*)

private lemma *NotNotD*[PLM-dest]:

$[\neg(\neg \varphi) \text{ in } v] \implies [\varphi \text{ in } v]$

using $\neg \neg E$ **by** *blast*

private lemma *ImplI*[PLM-intro]:

```

( $[\varphi \text{ in } v] \implies [\psi \text{ in } v] \implies [\varphi \rightarrow \psi \text{ in } v]$ )
using CP .
private lemma ImplE[PLM-elim, PLM-dest]:
 $[\varphi \rightarrow \psi \text{ in } v] \implies ([\varphi \text{ in } v] \implies [\psi \text{ in } v])$ 
using modus-ponens .
private lemma ImplS[PLM-subst]:
 $[\varphi \rightarrow \psi \text{ in } v] = ([\varphi \text{ in } v] \longrightarrow [\psi \text{ in } v])$ 
using ImplI ImplE by blast

private lemma NotI[PLM-intro]:
 $([\varphi \text{ in } v] \implies (\bigwedge \psi . [\psi \text{ in } v])) \implies [\neg \varphi \text{ in } v]$ 
using CP modus-tollens-2 by blast
private lemma NotE[PLM-elim, PLM-dest]:
 $[\neg \varphi \text{ in } v] \implies ([\varphi \text{ in } v] \longrightarrow (\forall \psi . [\psi \text{ in } v]))$ 
using  $\vee I(2) \vee E(3)$  by blast
private lemma NotS[PLM-subst]:
 $[\neg \varphi \text{ in } v] = ([\varphi \text{ in } v] \longrightarrow (\forall \psi . [\psi \text{ in } v]))$ 
using NotI NotE by blast

private lemma ConjI[PLM-intro]:
 $[[\varphi \text{ in } v]; [\psi \text{ in } v]] \implies [\varphi \ \& \ \psi \text{ in } v]$ 
using  $\&I$  by blast
private lemma ConjE[PLM-elim, PLM-dest]:
 $[\varphi \ \& \ \psi \text{ in } v] \implies (([\varphi \text{ in } v] \wedge [\psi \text{ in } v]))$ 
using CP &E by blast
private lemma ConjS[PLM-subst]:
 $[\varphi \ \& \ \psi \text{ in } v] = (([\varphi \text{ in } v] \wedge [\psi \text{ in } v]))$ 
using ConjI ConjE by blast

private lemma DisjI[PLM-intro]:
 $[\varphi \text{ in } v] \vee [\psi \text{ in } v] \implies [\varphi \vee \psi \text{ in } v]$ 
using  $\vee I$  by blast
private lemma DisjE[PLM-elim, PLM-dest]:
 $[\varphi \vee \psi \text{ in } v] \implies [\varphi \text{ in } v] \vee [\psi \text{ in } v]$ 
using CP  $\vee E(1)$  by blast
private lemma DisjS[PLM-subst]:
 $[\varphi \vee \psi \text{ in } v] = ([\varphi \text{ in } v] \vee [\psi \text{ in } v])$ 
using DisjI DisjE by blast

private lemma EquivI[PLM-intro]:
 $[[\varphi \text{ in } v] \implies [\psi \text{ in } v]; [\psi \text{ in } v] \implies [\varphi \text{ in } v]] \implies [\varphi \equiv \psi \text{ in } v]$ 
using CP  $\equiv I$  by blast
private lemma EquivE[PLM-elim, PLM-dest]:
 $[\varphi \equiv \psi \text{ in } v] \implies (([\varphi \text{ in } v] \longrightarrow [\psi \text{ in } v]) \wedge ([\psi \text{ in } v] \longrightarrow [\varphi \text{ in } v]))$ 
using  $\equiv E(1) \equiv E(2)$  by blast
private lemma EquivS[PLM-subst]:
 $[\varphi \equiv \psi \text{ in } v] = ([\varphi \text{ in } v] \longleftrightarrow [\psi \text{ in } v])$ 
using EquivI EquivE by blast

private lemma NotOrD[PLM-dest]:
 $\neg[\varphi \vee \psi \text{ in } v] \implies \neg[\varphi \text{ in } v] \wedge \neg[\psi \text{ in } v]$ 
using  $\vee I$  by blast
private lemma NotAndD[PLM-dest]:
 $\neg[\varphi \ \& \ \psi \text{ in } v] \implies \neg[\varphi \text{ in } v] \vee \neg[\psi \text{ in } v]$ 
using  $\&I$  by blast
private lemma NotEquivD[PLM-dest]:
 $\neg[\varphi \equiv \psi \text{ in } v] \implies [\varphi \text{ in } v] \neq [\psi \text{ in } v]$ 
by (meson NotI contraposition-1  $\equiv I$  vdash-properties-9)

private lemma BoxI[PLM-intro]:
 $(\bigwedge v . [\varphi \text{ in } v]) \implies [\Box \varphi \text{ in } v]$ 
using RN by blast
private lemma NotBoxD[PLM-dest]:

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 $\neg[\Box \varphi \text{ in } v] \implies (\exists v . \neg[\varphi \text{ in } v])$ 
using BoxI by blast

private lemma AllI[PLM-intro]:
   $(\bigwedge x . [\varphi x \text{ in } v]) \implies [\forall x . \varphi x \text{ in } v]$ 
  using rule-gen by blast
lemma NotAllD[PLM-dest]:
   $\neg[\forall x . \varphi x \text{ in } v] \implies (\exists x . \neg[\varphi x \text{ in } v])$ 
  using AllI by fastforce
end

lemma oth-class-taut-1-a[PLM]:
   $[\neg(\varphi \ \& \ \neg\varphi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-1-b[PLM]:
   $[\neg(\varphi \equiv \neg\varphi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-2[PLM]:
   $[\varphi \vee \neg\varphi \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-a[PLM]:
   $[(\varphi \ \& \ \varphi) \equiv \varphi \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-b[PLM]:
   $[(\varphi \ \& \ \psi) \equiv (\psi \ \& \ \varphi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-c[PLM]:
   $[(\varphi \ \& \ (\psi \ \& \ \chi)) \equiv ((\varphi \ \& \ \psi) \ \& \ \chi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-d[PLM]:
   $[(\varphi \vee \varphi) \equiv \varphi \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-e[PLM]:
   $[(\varphi \vee \psi) \equiv (\psi \vee \varphi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-f[PLM]:
   $[(\varphi \vee (\psi \vee \chi)) \equiv ((\varphi \vee \psi) \vee \chi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-g[PLM]:
   $[(\varphi \equiv \psi) \equiv (\psi \equiv \varphi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-3-i[PLM]:
   $[(\varphi \equiv (\psi \equiv \chi)) \equiv ((\varphi \equiv \psi) \equiv \chi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-4-a[PLM]:
   $[\varphi \equiv \varphi \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-4-b[PLM]:
   $[\varphi \equiv \neg\neg\varphi \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-5-a[PLM]:
   $[(\varphi \rightarrow \psi) \equiv \neg(\varphi \ \& \ \neg\psi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-5-b[PLM]:
   $[\neg(\varphi \rightarrow \psi) \equiv (\varphi \ \& \ \neg\psi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-5-c[PLM]:
   $[(\varphi \rightarrow \psi) \rightarrow ((\psi \rightarrow \chi) \rightarrow (\varphi \rightarrow \chi)) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-5-d[PLM]:
   $[(\varphi \equiv \psi) \equiv (\neg\varphi \equiv \neg\psi) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-5-e[PLM]:

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$[(\varphi \equiv \psi) \rightarrow ((\varphi \rightarrow \chi) \equiv (\psi \rightarrow \chi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-5-f*[*PLM*]:
 $[(\varphi \equiv \psi) \rightarrow ((\chi \rightarrow \varphi) \equiv (\chi \rightarrow \psi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-5-g*[*PLM*]:
 $[(\varphi \equiv \psi) \rightarrow ((\varphi \equiv \chi) \equiv (\psi \equiv \chi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-5-h*[*PLM*]:
 $[(\varphi \equiv \psi) \rightarrow ((\chi \equiv \varphi) \equiv (\chi \equiv \psi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-5-i*[*PLM*]:
 $[(\varphi \equiv \psi) \equiv ((\varphi \ \& \ \psi) \vee (\neg \varphi \ \& \ \neg \psi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-5-j*[*PLM*]:
 $[(\neg(\varphi \equiv \psi)) \equiv ((\varphi \ \& \ \neg \psi) \vee (\neg \varphi \ \& \ \psi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-5-k*[*PLM*]:
 $[(\varphi \rightarrow \psi) \equiv (\neg \varphi \vee \psi) \text{ in } v]$
by *PLM-solver*

lemma *oth-class-taut-6-a*[*PLM*]:
 $[(\varphi \ \& \ \psi) \equiv \neg(\neg \varphi \vee \neg \psi) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-6-b*[*PLM*]:
 $[(\varphi \vee \psi) \equiv \neg(\neg \varphi \ \& \ \neg \psi) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-6-c*[*PLM*]:
 $[\neg(\varphi \ \& \ \psi) \equiv (\neg \varphi \vee \neg \psi) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-6-d*[*PLM*]:
 $[\neg(\varphi \vee \psi) \equiv (\neg \varphi \ \& \ \neg \psi) \text{ in } v]$
by *PLM-solver*

lemma *oth-class-taut-7-a*[*PLM*]:
 $[(\varphi \ \& \ (\psi \vee \chi)) \equiv ((\varphi \ \& \ \psi) \vee (\varphi \ \& \ \chi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-7-b*[*PLM*]:
 $[(\varphi \vee (\psi \ \& \ \chi)) \equiv ((\varphi \vee \psi) \ \& \ (\varphi \vee \chi)) \text{ in } v]$
by *PLM-solver*

lemma *oth-class-taut-8-a*[*PLM*]:
 $[(\varphi \ \& \ \psi) \rightarrow \chi) \rightarrow (\varphi \rightarrow (\psi \rightarrow \chi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-8-b*[*PLM*]:
 $[(\varphi \rightarrow (\psi \rightarrow \chi)) \rightarrow ((\varphi \ \& \ \psi) \rightarrow \chi) \text{ in } v]$
by *PLM-solver*

lemma *oth-class-taut-9-a*[*PLM*]:
 $[(\varphi \ \& \ \psi) \rightarrow \varphi \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-9-b*[*PLM*]:
 $[(\varphi \ \& \ \psi) \rightarrow \psi \text{ in } v]$
by *PLM-solver*

lemma *oth-class-taut-10-a*[*PLM*]:
 $[\varphi \rightarrow (\psi \rightarrow (\varphi \ \& \ \psi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-10-b*[*PLM*]:
 $[(\varphi \rightarrow (\psi \rightarrow \chi)) \equiv (\psi \rightarrow (\varphi \rightarrow \chi)) \text{ in } v]$
by *PLM-solver*
lemma *oth-class-taut-10-c*[*PLM*]:
 $[(\varphi \rightarrow \psi) \rightarrow ((\varphi \rightarrow \chi) \rightarrow (\varphi \rightarrow (\psi \ \& \ \chi))) \text{ in } v]$


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  by PLM-solver
lemma oth-class-taut-10-d[PLM]:
   $[(\varphi \rightarrow \chi) \rightarrow ((\psi \rightarrow \chi) \rightarrow ((\varphi \vee \psi) \rightarrow \chi)) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-10-e[PLM]:
   $[(\varphi \rightarrow \psi) \rightarrow ((\chi \rightarrow \Theta) \rightarrow ((\varphi \& \chi) \rightarrow (\psi \& \Theta))) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-10-f[PLM]:
   $[(\varphi \& \psi) \equiv (\varphi \& \chi) \equiv (\varphi \rightarrow (\psi \equiv \chi)) \text{ in } v]$ 
  by PLM-solver
lemma oth-class-taut-10-g[PLM]:
   $[(\varphi \& \psi) \equiv (\chi \& \psi) \equiv (\psi \rightarrow (\varphi \equiv \chi)) \text{ in } v]$ 
  by PLM-solver

attribute-setup equiv-lr = <<
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm  $\equiv E(1)$ }))
  >>

attribute-setup equiv-rl = <<
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm  $\equiv E(2)$ }))
  >>

attribute-setup equiv-sym = <<
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm oth-class-taut-3-g[equiv-lr]}))
  >>

attribute-setup conj1 = <<
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm  $\& E(1)$ }))
  >>

attribute-setup conj2 = <<
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm  $\& E(2)$ }))
  >>

attribute-setup conj-sym = <<
  Scan.succeed (Thm.rule-attribute []
    (fn - => fn thm => thm RS @ {thm oth-class-taut-3-b[equiv-lr]}))
  >>

```

9.7 Identity

Remark 22. For the following proofs first the definitions for the respective identities have to be expanded. They are defined directly in the embedded logic, though, so the proofs are still independent of the meta-logic.

```

lemma id-eq-prop-prop-1[PLM]:
   $[(F::\Pi_1) = F \text{ in } v]$ 
  unfolding identity-defs by PLM-solver
lemma id-eq-prop-prop-2[PLM]:
   $[(F::\Pi_1) = G \rightarrow (G = F) \text{ in } v]$ 
  by (meson id-eq-prop-prop-1 CP ded-thm-cor-3 l-identity[axiom-instance])
lemma id-eq-prop-prop-3[PLM]:
   $[(F::\Pi_1) = G \& (G = H) \rightarrow (F = H) \text{ in } v]$ 
  by (metis l-identity[axiom-instance] ded-thm-cor-4 CP &E)
lemma id-eq-prop-prop-4-a[PLM]:
   $[(F::\Pi_2) = F \text{ in } v]$ 
  unfolding identity-defs by PLM-solver
lemma id-eq-prop-prop-4-b[PLM]:

```

```

[[ $(F::\Pi_3) = F$  in  $v$ ]
unfolding identity-defs by PLM-solver
lemma id-eq-prop-prop-5-a[PLM]:
[[ $((F::\Pi_2) = G) \rightarrow (G = F)$  in  $v$ ]
by (meson id-eq-prop-prop-4-a CP ded-thm-cor-3 l-identity[axiom-instance])
lemma id-eq-prop-prop-5-b[PLM]:
[[ $((F::\Pi_3) = G) \rightarrow (G = F)$  in  $v$ ]
by (meson id-eq-prop-prop-4-b CP ded-thm-cor-3 l-identity[axiom-instance])
lemma id-eq-prop-prop-6-a[PLM]:
[[ $((F::\Pi_2) = G) \ \& \ (G = H) \rightarrow (F = H)$  in  $v$ ]
by (metis l-identity[axiom-instance] ded-thm-cor-4 CP &E)
lemma id-eq-prop-prop-6-b[PLM]:
[[ $((F::\Pi_3) = G) \ \& \ (G = H) \rightarrow (F = H)$  in  $v$ ]
by (metis l-identity[axiom-instance] ded-thm-cor-4 CP &E)
lemma id-eq-prop-prop-7[PLM]:
[[ $(p::\Pi_0) = p$  in  $v$ ]
unfolding identity-defs by PLM-solver
lemma id-eq-prop-prop-7-b[PLM]:
[[ $(p::o) = p$  in  $v$ ]
unfolding identity-defs by PLM-solver
lemma id-eq-prop-prop-8[PLM]:
[[ $((p::\Pi_0) = q) \rightarrow (q = p)$  in  $v$ ]
by (meson id-eq-prop-prop-7 CP ded-thm-cor-3 l-identity[axiom-instance])
lemma id-eq-prop-prop-8-b[PLM]:
[[ $((p::o) = q) \rightarrow (q = p)$  in  $v$ ]
by (meson id-eq-prop-prop-7-b CP ded-thm-cor-3 l-identity[axiom-instance])
lemma id-eq-prop-prop-9[PLM]:
[[ $((p::\Pi_0) = q) \ \& \ (q = r) \rightarrow (p = r)$  in  $v$ ]
by (metis l-identity[axiom-instance] ded-thm-cor-4 CP &E)
lemma id-eq-prop-prop-9-b[PLM]:
[[ $((p::o) = q) \ \& \ (q = r) \rightarrow (p = r)$  in  $v$ ]
by (metis l-identity[axiom-instance] ded-thm-cor-4 CP &E)

lemma eq-E-simple-1[PLM]:
[[ $(x =_E y) \equiv ((O!,x) \ \& \ (O!,y)) \ \& \ \Box(\forall F. (F,x) \equiv (F,y))$  in  $v$ ]
proof (rule  $\equiv I$ ; rule CP)
assume  $1: [x =_E y$  in  $v]$ 
have  $[\forall x y. ((x^P) =_E (y^P)) \equiv ((O!,x^P) \ \& \ (O!,y^P))$ 
&  $\Box(\forall F. (F,x^P) \equiv (F,y^P))$  in  $v]$ 
unfolding identityE-infix-def identityE-def
apply (rule lambda-predicates-2-2[axiom-universal, axiom-universal, axiom-instance])
by (rule IsPropositional-intros)
moreover have  $[\exists \alpha. (\alpha^P) = x$  in  $v]$ 
apply (rule cqt-5-mod[where  $\psi = \lambda x. x =_E y$ , axiom-instance, deduction])
unfolding identityE-infix-def
apply (rule SimpleExOrEnc.intros)
using  $1$  unfolding identityE-infix-def by auto
moreover have  $[\exists \beta. (\beta^P) = y$  in  $v]$ 
apply (rule cqt-5-mod[where  $\psi = \lambda y. x =_E y$ , axiom-instance, deduction])
unfolding identityE-infix-def
apply (rule SimpleExOrEnc.intros) using  $1$ 
unfolding identityE-infix-def by auto
ultimately have  $[(x =_E y) \equiv ((O!,x) \ \& \ (O!,y))$ 
&  $\Box(\forall F. (F,x) \equiv (F,y))$  in  $v]$ 
using cqt-1-κ[axiom-instance, deduction, deduction] by meson
thus  $[(O!,x) \ \& \ (O!,y) \ \& \ \Box(\forall F. (F,x) \equiv (F,y))$  in  $v]$ 
using  $1 \equiv E(1)$  by blast
next
assume  $1: [(O!,x) \ \& \ (O!,y) \ \& \ \Box(\forall F. (F,x) \equiv (F,y))$  in  $v]$ 
have  $[\forall x y. ((x^P) =_E (y^P)) \equiv ((O!,x^P) \ \& \ (O!,y^P))$ 
&  $\Box(\forall F. (F,x^P) \equiv (F,y^P))$  in  $v]$ 
unfolding identityE-def identityE-infix-def
apply (rule lambda-predicates-2-2[axiom-universal, axiom-universal, axiom-instance])

```

```

    by (rule IsPropositional-intros)
  moreover have  $[\exists \alpha . (\alpha^P) = x \text{ in } v]$ 
    apply (rule cqt-5-mod[where  $\psi = \lambda x . \langle O!, x \rangle$ , axiom-instance, deduction])
    apply (rule SimpleExOrEnc.intros)
    using 1[conj1, conj1] by auto
  moreover have  $[\exists \beta . (\beta^P) = y \text{ in } v]$ 
    apply (rule cqt-5-mod[where  $\psi = \lambda y . \langle O!, y \rangle$ , axiom-instance, deduction])
    apply (rule SimpleExOrEnc.intros)
    using 1[conj1, conj2] by auto
  ultimately have  $[(x =_E y) \equiv (\langle O!, x \rangle \ \& \ \langle O!, y \rangle)$ 
     $\ \& \ \Box(\forall F . \langle F, x \rangle \equiv \langle F, y \rangle)) \text{ in } v]$ 
    using cqt-1- $\kappa$ [axiom-instance, deduction, deduction] by meson
  thus  $[(x =_E y) \text{ in } v]$  using 1  $\equiv E(2)$  by blast
qed
lemma eq-E-simple-2[PLM]:
 $[(x =_E y) \rightarrow (x = y) \text{ in } v]$ 
  unfolding identity-defs by PLM-solver
lemma eq-E-simple-3[PLM]:
 $[(x = y) \equiv (((\langle O!, x \rangle \ \& \ \langle O!, y \rangle \ \& \ \Box(\forall F . \langle F, x \rangle \equiv \langle F, y \rangle))$ 
 $\ \vee \ (\langle A!, x \rangle \ \& \ \langle A!, y \rangle \ \& \ \Box(\forall F . \langle x, F \rangle \equiv \langle y, F \rangle))) \text{ in } v]$ 
  using eq-E-simple-1
  apply cut-tac unfolding identity-defs
  by PLM-solver

lemma id-eq-obj-1[PLM]:  $[(x^P) = (x^P) \text{ in } v]$ 
  proof -
    have  $[(\Diamond \langle E!, x^P \rangle) \vee (\neg \Diamond \langle E!, x^P \rangle) \text{ in } v]$ 
      using PLM.oth-class-taut-2 by simp
    hence  $[(\Diamond \langle E!, x^P \rangle) \text{ in } v] \vee [(\neg \Diamond \langle E!, x^P \rangle) \text{ in } v]$ 
      using CP  $\vee E(1)$  by blast
    moreover {
      assume  $[(\Diamond \langle E!, x^P \rangle) \text{ in } v]$ 
      hence  $[(\lambda x . \Diamond \langle E!, x^P \rangle, x^P) \text{ in } v]$ 
        apply (rule lambda-predicates-2-1[axiom-instance, equiv-rl, rotated])
        by (rule IsPropositional-intros)+
      hence  $[(\lambda x . \Diamond \langle E!, x^P \rangle, x^P) \ \& \ (\lambda x . \Diamond \langle E!, x^P \rangle, x^P)]$ 
         $\ \& \ \Box(\forall F . \langle F, x^P \rangle \equiv \langle F, x^P \rangle) \text{ in } v]$ 
        apply cut-tac by PLM-solver
      hence  $[(x^P) =_E (x^P) \text{ in } v]$ 
        using eq-E-simple-1[equiv-rl] unfolding Ordinary-def by fast
    }
    moreover {
      assume  $[(\neg \Diamond \langle E!, x^P \rangle) \text{ in } v]$ 
      hence  $[(\lambda x . \neg \Diamond \langle E!, x^P \rangle, x^P) \text{ in } v]$ 
        apply (rule lambda-predicates-2-1[axiom-instance, equiv-rl, rotated])
        by (rule IsPropositional-intros)+
      hence  $[(\lambda x . \neg \Diamond \langle E!, x^P \rangle, x^P) \ \& \ (\lambda x . \neg \Diamond \langle E!, x^P \rangle, x^P)]$ 
         $\ \& \ \Box(\forall F . \langle x^P, F \rangle \equiv \langle x^P, F \rangle) \text{ in } v]$ 
        apply cut-tac by PLM-solver
    }
    ultimately show ?thesis unfolding identity-defs Ordinary-def Abstract-def
      using  $\vee I$  by blast
  qed
lemma id-eq-obj-2[PLM]:
 $[(x^P) = (y^P) \rightarrow ((y^P) = (x^P)) \text{ in } v]$ 
  by (meson l-identity[axiom-instance] id-eq-obj-1 CP ded-thm-cor-3)
lemma id-eq-obj-3[PLM]:
 $[(x^P) = (y^P) \ \& \ (y^P) = (z^P) \rightarrow ((x^P) = (z^P)) \text{ in } v]$ 
  by (metis l-identity[axiom-instance] ded-thm-cor-4 CP  $\& E$ )
end

```

Remark 23. To unify the statements of the properties of equality a type class is introduced.

`class id-eq = quantifiable-and-identifiable +`

```

assumes id-eq-1:  $[(x :: 'a) = x \text{ in } v]$ 
assumes id-eq-2:  $[(x :: 'a) = y \rightarrow (y = x) \text{ in } v]$ 
assumes id-eq-3:  $[(x :: 'a) = y \ \& \ (y = z) \rightarrow (x = z) \text{ in } v]$ 

```

instantiation $\nu :: id\text{-eq}$

begin

instance proof

fix $x :: \nu$ **and** v

show $[x = x \text{ in } v]$

using *PLM.id-eq-obj-1*

by (*simp add: identity- ν -def*)

next

fix $x\ y :: \nu$ **and** v

show $[x = y \rightarrow y = x \text{ in } v]$

using *PLM.id-eq-obj-2*

by (*simp add: identity- ν -def*)

next

fix $x\ y\ z :: \nu$ **and** v

show $[(x = y) \ \& \ (y = z)) \rightarrow x = z \text{ in } v]$

using *PLM.id-eq-obj-3*

by (*simp add: identity- ν -def*)

qed

end

instantiation $\circ :: id\text{-eq}$

begin

instance proof

fix $x :: \circ$ **and** v

show $[x = x \text{ in } v]$

using *PLM.id-eq-prop-prop-7* .

next

fix $x\ y :: \circ$ **and** v

show $[x = y \rightarrow y = x \text{ in } v]$

using *PLM.id-eq-prop-prop-8* .

next

fix $x\ y\ z :: \circ$ **and** v

show $[(x = y) \ \& \ (y = z)) \rightarrow x = z \text{ in } v]$

using *PLM.id-eq-prop-prop-9* .

qed

end

instantiation $\Pi_1 :: id\text{-eq}$

begin

instance proof

fix $x :: \Pi_1$ **and** v

show $[x = x \text{ in } v]$

using *PLM.id-eq-prop-prop-1* .

next

fix $x\ y :: \Pi_1$ **and** v

show $[x = y \rightarrow y = x \text{ in } v]$

using *PLM.id-eq-prop-prop-2* .

next

fix $x\ y\ z :: \Pi_1$ **and** v

show $[(x = y) \ \& \ (y = z)) \rightarrow x = z \text{ in } v]$

using *PLM.id-eq-prop-prop-3* .

qed

end

instantiation $\Pi_2 :: id\text{-eq}$

begin

instance proof

fix $x :: \Pi_2$ **and** v

show $[x = x \text{ in } v]$

```

    using PLM.id-eq-prop-prop-4-a .
next
  fix x y ::  $\Pi_2$  and v
  show  $[x = y \rightarrow y = x \text{ in } v]$ 
    using PLM.id-eq-prop-prop-5-a .
next
  fix x y z ::  $\Pi_2$  and v
  show  $[(x = y) \ \& \ (y = z) \rightarrow x = z \text{ in } v]$ 
    using PLM.id-eq-prop-prop-6-a .
qed
end

instantiation  $\Pi_3 :: \text{id-eq}$ 
begin
  instance proof
    fix x ::  $\Pi_3$  and v
    show  $[x = x \text{ in } v]$ 
      using PLM.id-eq-prop-prop-4-b .
  next
    fix x y ::  $\Pi_3$  and v
    show  $[x = y \rightarrow y = x \text{ in } v]$ 
      using PLM.id-eq-prop-prop-5-b .
  next
    fix x y z ::  $\Pi_3$  and v
    show  $[(x = y) \ \& \ (y = z) \rightarrow x = z \text{ in } v]$ 
      using PLM.id-eq-prop-prop-6-b .
  qed
end

context PLM
begin
  lemma id-eq-1[PLM]:
     $[(x :: 'a :: \text{id-eq}) = x \text{ in } v]$ 
    using id-eq-1 .
  lemma id-eq-2[PLM]:
     $[(x :: 'a :: \text{id-eq}) = y \rightarrow (y = x) \text{ in } v]$ 
    using id-eq-2 .
  lemma id-eq-3[PLM]:
     $[(x :: 'a :: \text{id-eq}) = y \ \& \ (y = z) \rightarrow (x = z) \text{ in } v]$ 
    using id-eq-3 .

  attribute-setup eq-sym = ⟨⟨
    Scan.succeed (Thm.rule-attribute []
      (fn - => fn thm => thm RS @ {thm id-eq-2[deduction]}))
    ⟩⟩

  lemma all-self-eq-1[PLM]:
     $[\Box (\forall \alpha :: 'a :: \text{id-eq} . \alpha = \alpha) \text{ in } v]$ 
    by PLM-solver
  lemma all-self-eq-2[PLM]:
     $[\forall \alpha :: 'a :: \text{id-eq} . \Box (\alpha = \alpha) \text{ in } v]$ 
    by PLM-solver

  lemma t-id-t-proper-1[PLM]:
     $[\tau = \tau' \rightarrow (\exists \beta . (\beta^P) = \tau) \text{ in } v]$ 
    proof (rule CP)
      assume  $[\tau = \tau' \text{ in } v]$ 
      moreover {
        assume  $[\tau =_E \tau' \text{ in } v]$ 
        hence  $[\exists \beta . (\beta^P) = \tau \text{ in } v]$ 
        apply cut-tac
        apply (rule cqt-5-mod[where  $\psi = \lambda \tau . \tau =_E \tau'$ , axiom-instance, deduction])
      }
    qed

```

```

      subgoal unfolding identity-defs by (rule SimpleExOrEnc.intros)
    by simp
  }
  moreover {
    assume [( $\lambda A!.\tau$ ) & ( $\lambda A!.\tau'$ ) &  $\Box(\forall F. \llbracket \tau, F \rrbracket \equiv \llbracket \tau', F \rrbracket)$ ] in v]
    hence [ $\exists \beta. (\beta^P) = \tau$ ] in v]
    apply cut-tac
    apply (rule cqt-5-mod[where  $\psi = \lambda \tau. (\lambda A!.\tau)$ , axiom-instance, deduction])
    subgoal unfolding identity-defs by (rule SimpleExOrEnc.intros)
    by PLM-solver
  }
  ultimately show [ $\exists \beta. (\beta^P) = \tau$ ] in v] unfolding identity $_{\kappa}$ -def
    using intro-elim-4-b reductio-aa-1 by blast
qed

```

```

lemma t-id-t-proper-2[PLM]: [ $\tau = \tau' \rightarrow (\exists \beta. (\beta^P) = \tau')$ ] in v]
proof (rule CP)
  assume [ $\tau = \tau'$ ] in v]
  moreover {
    assume [ $\tau =_E \tau'$ ] in v]
    hence [ $\exists \beta. (\beta^P) = \tau'$ ] in v]
    apply cut-tac
    apply (rule cqt-5-mod[where  $\psi = \lambda \tau'. \tau =_E \tau'$ , axiom-instance, deduction])
    subgoal unfolding identity-defs by (rule SimpleExOrEnc.intros)
    by simp
  }
  moreover {
    assume [( $\lambda A!.\tau$ ) & ( $\lambda A!.\tau'$ ) &  $\Box(\forall F. \llbracket \tau, F \rrbracket \equiv \llbracket \tau', F \rrbracket)$ ] in v]
    hence [ $\exists \beta. (\beta^P) = \tau'$ ] in v]
    apply cut-tac
    apply (rule cqt-5-mod[where  $\psi = \lambda \tau. (\lambda A!.\tau)$ , axiom-instance, deduction])
    subgoal unfolding identity-defs by (rule SimpleExOrEnc.intros)
    by PLM-solver
  }
  ultimately show [ $\exists \beta. (\beta^P) = \tau'$ ] in v] unfolding identity $_{\kappa}$ -def
    using intro-elim-4-b reductio-aa-1 by blast
qed

```

```

lemma id-nec[PLM]: [( $(\alpha::'a::id-eq) = (\beta)$ )  $\equiv \Box((\alpha) = (\beta))$ ] in v]
  apply (rule  $\equiv I$ )
  using l-identity[where  $\varphi = (\lambda \beta. \Box((\alpha) = (\beta)))$ , axiom-instance]
    id-eq-1 RN ded-thm-cor-4 unfolding identity- $\nu$ -def
  apply blast
  using qml-2[axiom-instance] by blast

```

```

lemma id-nec-desc[PLM]:
  [( $(\lambda x. \varphi x) = (\lambda x. \psi x)$ )  $\equiv \Box((\lambda x. \varphi x) = (\lambda x. \psi x))$ ] in v]
proof (cases [( $\exists \alpha. (\alpha^P) = (\lambda x. \varphi x)$ ] in v]  $\wedge$  [( $\exists \beta. (\beta^P) = (\lambda x. \psi x)$ ] in v])
  assume [( $\exists \alpha. (\alpha^P) = (\lambda x. \varphi x)$ ] in v]  $\wedge$  [( $\exists \beta. (\beta^P) = (\lambda x. \psi x)$ ] in v]
  then obtain  $\alpha$  and  $\beta$  where
    [( $\alpha^P$ ) = ( $\lambda x. \varphi x$ )] in v]  $\wedge$  [( $\beta^P$ ) = ( $\lambda x. \psi x$ )] in v]
    apply cut-tac unfolding conn-defs by PLM-solver
  moreover {
    moreover have [( $\alpha = \beta \equiv \Box((\alpha) = (\beta))$ ] in v] by PLM-solver
    ultimately have [( $(\lambda x. \varphi x) = (\beta^P) \equiv \Box((\lambda x. \varphi x) = (\beta^P))$ ] in v]
      using l-identity[where  $\varphi = \lambda \alpha. (\alpha) = (\beta^P) \equiv \Box((\alpha) = (\beta^P))$ , axiom-instance]
      modus-ponens unfolding identity- $\nu$ -def by metis
  }
  ultimately show ?thesis
    using l-identity[where  $\varphi = \lambda \alpha. (\lambda x. \varphi x) = (\alpha) \equiv \Box((\lambda x. \varphi x) = (\alpha))$ , axiom-instance]
      modus-ponens by metis
next

```

```

assume  $\neg[(\exists \alpha. (\alpha^P) = (\iota x . \varphi x)) \text{ in } v] \wedge [(\exists \beta. (\beta^P) = (\iota x . \psi x)) \text{ in } v]$ 
hence  $\neg[(\lambda A! . (\iota x . \varphi x)) \text{ in } v] \wedge \neg[(\iota x . \varphi x) =_E (\iota x . \psi x) \text{ in } v]$ 
 $\vee \neg[(\lambda A! . (\iota x . \psi x)) \text{ in } v] \wedge \neg[(\iota x . \varphi x) =_E (\iota x . \psi x) \text{ in } v]$ 
unfolding identityE-infix-def
using cqt-5[axiom-instance] PLM.contraposition-1 SimpleExOrEnc.intros
 $\text{vdash-properties-10}$  by meson
hence  $\neg[(\iota x . \varphi x) = (\iota x . \psi x) \text{ in } v]$ 
apply cut-tac unfolding identity-defs by PLM-solver
thus ?thesis apply cut-tac apply PLM-solver
using qml-2[axiom-instance, deduction] by auto
qed

```

9.8 Quantification

— TODO: think about the distinction in PM here

lemma *rule-ui[PLM,PLM-elim,PLM-dest]:*

$[\forall \alpha . \varphi \alpha \text{ in } v] \implies [\varphi \beta \text{ in } v]$

by (*meson cqt-1[axiom-instance, deduction]*)

lemmas $\forall E = \text{rule-ui}$

lemma *rule-ui-2[PLM,PLM-elim,PLM-dest]:*

$[[\forall \alpha . \varphi (\alpha^P) \text{ in } v]; [\exists \alpha . (\alpha)^P = \beta \text{ in } v]] \implies [\varphi \beta \text{ in } v]$

using *cqt-1- κ [axiom-instance, deduction, deduction] by blast*

lemma *cqt-orig-1[PLM]:*

$[(\forall \alpha . \varphi \alpha) \rightarrow \varphi \beta \text{ in } v]$

by *PLM-solver*

lemma *cqt-orig-2[PLM]:*

$[(\forall \alpha . \varphi \rightarrow \psi \alpha) \rightarrow (\varphi \rightarrow (\forall \alpha . \psi \alpha)) \text{ in } v]$

by *PLM-solver*

lemma *universal[PLM]:*

$(\bigwedge \alpha . [\varphi \alpha \text{ in } v]) \implies [\forall \alpha . \varphi \alpha \text{ in } v]$

using *rule-gen .*

lemmas $\forall I = \text{universal}$

lemma *cqt-basic-1[PLM]:*

$[(\forall \alpha . (\forall \beta . \varphi \alpha \beta)) \equiv (\forall \beta . (\forall \alpha . \varphi \alpha \beta)) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-2[PLM]:*

$[(\forall \alpha . \varphi \alpha \equiv \psi \alpha) \equiv ((\forall \alpha . \varphi \alpha \rightarrow \psi \alpha) \ \& \ (\forall \alpha . \psi \alpha \rightarrow \varphi \alpha)) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-3[PLM]:*

$[(\forall \alpha . \varphi \alpha \equiv \psi \alpha) \rightarrow ((\forall \alpha . \varphi \alpha) \equiv (\forall \alpha . \psi \alpha)) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-4[PLM]:*

$[(\forall \alpha . \varphi \alpha \ \& \ \psi \alpha) \equiv ((\forall \alpha . \varphi \alpha) \ \& \ (\forall \alpha . \psi \alpha)) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-6[PLM]:*

$[(\forall \alpha . (\forall \alpha . \varphi \alpha)) \equiv (\forall \alpha . \varphi \alpha) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-7[PLM]:*

$[(\varphi \rightarrow (\forall \alpha . \psi \alpha)) \equiv (\forall \alpha . (\varphi \rightarrow \psi \alpha)) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-8[PLM]:*

$[((\forall \alpha . \varphi \alpha) \vee (\forall \alpha . \psi \alpha)) \rightarrow (\forall \alpha . (\varphi \alpha \vee \psi \alpha)) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-9[PLM]:*

$[((\forall \alpha . \varphi \alpha \rightarrow \psi \alpha) \ \& \ (\forall \alpha . \psi \alpha \rightarrow \chi \alpha)) \rightarrow (\forall \alpha . \varphi \alpha \rightarrow \chi \alpha) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-10[PLM]:*

$[((\forall \alpha . \varphi \alpha \equiv \psi \alpha) \ \& \ (\forall \alpha . \psi \alpha \equiv \chi \alpha)) \rightarrow (\forall \alpha . \varphi \alpha \equiv \chi \alpha) \text{ in } v]$

by *PLM-solver*

lemma *cqt-basic-11*[*PLM*]:
 $[(\forall \alpha. \varphi \alpha \equiv \psi \alpha) \equiv (\forall \alpha. \psi \alpha \equiv \varphi \alpha) \text{ in } v]$
by *PLM-solver*

lemma *cqt-basic-12*[*PLM*]:
 $[(\forall \alpha. \varphi \alpha) \equiv (\forall \beta. \varphi \beta) \text{ in } v]$
by *PLM-solver*

lemma *existential*[*PLM*,*PLM-intro*]:
 $[\varphi \alpha \text{ in } v] \implies [\exists \alpha. \varphi \alpha \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemmas $\exists I = \text{existential}$

lemma *instantiation*-[*PLM*,*PLM-elim*,*PLM-dest*]:
 $[[\exists \alpha. \varphi \alpha \text{ in } v]; (\bigwedge \alpha. [\varphi \alpha \text{ in } v] \implies [\psi \text{ in } v])] \implies [\psi \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *Instantiate*:
assumes $[\exists x. \varphi x \text{ in } v]$
obtains x **where** $[\varphi x \text{ in } v]$
apply (*insert assms*) **unfolding** *exists-def* **by** *PLM-solver*

lemmas $\exists E = \text{Instantiate}$

lemma *cqt-further-1*[*PLM*]:
 $[(\forall \alpha. \varphi \alpha) \rightarrow (\exists \alpha. \varphi \alpha) \text{ in } v]$
by *PLM-solver*

lemma *cqt-further-2*[*PLM*]:
 $[(\neg(\forall \alpha. \varphi \alpha)) \equiv (\exists \alpha. \neg \varphi \alpha) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *cqt-further-3*[*PLM*]:
 $[(\forall \alpha. \varphi \alpha) \equiv \neg(\exists \alpha. \neg \varphi \alpha) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *cqt-further-4*[*PLM*]:
 $[(\neg(\exists \alpha. \varphi \alpha)) \equiv (\forall \alpha. \neg \varphi \alpha) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *cqt-further-5*[*PLM*]:
 $[(\exists \alpha. \varphi \alpha \ \& \ \psi \alpha) \rightarrow ((\exists \alpha. \varphi \alpha) \ \& \ (\exists \alpha. \psi \alpha)) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *cqt-further-6*[*PLM*]:
 $[(\exists \alpha. \varphi \alpha \vee \psi \alpha) \equiv ((\exists \alpha. \varphi \alpha) \vee (\exists \alpha. \psi \alpha)) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *cqt-further-10*[*PLM*]:
 $[(\varphi(\alpha::'a::id\text{-eq}) \ \& \ (\forall \beta. \varphi \beta \rightarrow \beta = \alpha)) \equiv (\forall \beta. \varphi \beta \equiv \beta = \alpha) \text{ in } v]$
apply *PLM-solver*
using *l-identity*[*axiom-instance*, *deduction*, *deduction*] *id-eq-2*[*deduction*]
apply *blast*
using *id-eq-1* **by** *auto*

lemma *cqt-further-11*[*PLM*]:
 $[((\forall \alpha. \varphi \alpha) \ \& \ (\forall \alpha. \psi \alpha)) \rightarrow (\forall \alpha. \varphi \alpha \equiv \psi \alpha) \text{ in } v]$
by *PLM-solver*

lemma *cqt-further-12*[*PLM*]:
 $[((\neg(\exists \alpha. \varphi \alpha)) \ \& \ (\neg(\exists \alpha. \psi \alpha))) \rightarrow (\forall \alpha. \varphi \alpha \equiv \psi \alpha) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *cqt-further-13*[*PLM*]:
 $[((\exists \alpha. \varphi \alpha) \ \& \ (\neg(\exists \alpha. \psi \alpha))) \rightarrow (\neg(\forall \alpha. \varphi \alpha \equiv \psi \alpha)) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *cqt-further-14*[*PLM*]:
 $[(\exists \alpha. \exists \beta. \varphi \alpha \beta) \equiv (\exists \beta. \exists \alpha. \varphi \alpha \beta) \text{ in } v]$
unfolding *exists-def* **by** *PLM-solver*

lemma *nec-exist-unique*[*PLM*]:
 $[(\forall x. \varphi x \rightarrow \Box(\varphi x)) \rightarrow ((\exists !x. \varphi x) \rightarrow (\exists !x. \Box(\varphi x))) \text{ in } v]$
proof (*rule CP*)
assume $a: [\forall x. \varphi x \rightarrow \Box \varphi x \text{ in } v]$
show $[(\exists !x. \varphi x) \rightarrow (\exists !x. \Box \varphi x) \text{ in } v]$


```

proof (rule CP)
  assume  $[(\exists !x. \varphi x) \text{ in } v]$ 
  hence  $[\exists \alpha. \varphi \alpha \ \& \ (\forall \beta. \varphi \beta \rightarrow \beta = \alpha) \text{ in } v]$ 
    by (simp only: exists-unique-def)
  then obtain  $\alpha$  where 1:
     $[\varphi \alpha \ \& \ (\forall \beta. \varphi \beta \rightarrow \beta = \alpha) \text{ in } v]$ 
    by (rule  $\exists E$ )
  {
    fix  $\beta$ 
    have  $[\Box \varphi \beta \rightarrow \beta = \alpha \text{ in } v]$ 
      using 1 &E(2) qml-2[axiom-instance]
      ded-thm-cor-3  $\forall E$  by fastforce
  }
  hence  $[\forall \beta. \Box \varphi \beta \rightarrow \beta = \alpha \text{ in } v]$  by (rule  $\forall I$ )
  moreover have  $[\Box(\varphi \alpha) \text{ in } v]$ 
    using 1 &E(1) a vdash-properties-10 cqt-orig-1[deduction]
    by fast
  ultimately have  $[\exists \alpha. \Box(\varphi \alpha) \ \& \ (\forall \beta. \Box \varphi \beta \rightarrow \beta = \alpha) \text{ in } v]$ 
    using &I  $\exists I$  by fast
  thus  $[(\exists !x. \Box \varphi x) \text{ in } v]$ 
    unfolding exists-unique-def by assumption
qed
qed

```

9.9 Actuality and Descriptions

```

lemma nec-imp-act[PLM]:  $[\Box \varphi \rightarrow \mathcal{A}\varphi \text{ in } v]$ 
  apply (rule CP)
  using qml-act-2[axiom-instance, equiv-lr]
    qml-2[axiom-actualization, axiom-instance]
    logic-actual-nec-2[axiom-instance, equiv-lr, deduction]
  by blast
lemma act-conj-act-1[PLM]:
   $[\mathcal{A}(\mathcal{A}\varphi \rightarrow \varphi) \text{ in } v]$ 
  using equiv-def logic-actual-nec-2[axiom-instance]
    logic-actual-nec-4[axiom-instance] &E(2)  $\equiv E(2)$ 
  by metis
lemma act-conj-act-2[PLM]:
   $[\mathcal{A}(\varphi \rightarrow \mathcal{A}\varphi) \text{ in } v]$ 
  using logic-actual-nec-2[axiom-instance] qml-act-1[axiom-instance]
    ded-thm-cor-3  $\equiv E(2)$  nec-imp-act
  by blast
lemma act-conj-act-3[PLM]:
   $[(\mathcal{A}\varphi \ \& \ \mathcal{A}\psi) \rightarrow \mathcal{A}(\varphi \ \& \ \psi) \text{ in } v]$ 
  unfolding conn-defs
  by (metis logic-actual-nec-2[axiom-instance]
    logic-actual-nec-1[axiom-instance]
     $\equiv E(2)$  CP  $\equiv E(4)$  reductio-aa-2
    vdash-properties-10)
lemma act-conj-act-4[PLM]:
   $[\mathcal{A}(\mathcal{A}\varphi \equiv \varphi) \text{ in } v]$ 
  unfolding equiv-def
  by (PLM-solver PLM-intro: act-conj-act-3[where  $\varphi = \mathcal{A}\varphi \rightarrow \varphi$ 
    and  $\psi = \varphi \rightarrow \mathcal{A}\varphi$ , deduction])
lemma closure-act-1a[PLM]:
   $[\mathcal{A}\mathcal{A}(\mathcal{A}\varphi \equiv \varphi) \text{ in } v]$ 
  using logic-actual-nec-4[axiom-instance]
    act-conj-act-4  $\equiv E(1)$ 
  by blast
lemma closure-act-1b[PLM]:
   $[\mathcal{A}\mathcal{A}\mathcal{A}(\mathcal{A}\varphi \equiv \varphi) \text{ in } v]$ 
  using logic-actual-nec-4[axiom-instance]
    act-conj-act-4  $\equiv E(1)$ 

```

```

by blast
lemma closure-act-1c[PLM]:
  [AAAA(Aφ ≡ φ) in v]
  using logic-actual-nec-4[axiom-instance]
    act-conj-act-4 ≡ E(1)
  by blast
lemma closure-act-2[PLM]:
  [∀ α. A(A(φ α) ≡ φ α) in v]
  by PLM-solver

lemma closure-act-3[PLM]:
  [A(∀ α. A(φ α) ≡ φ α) in v]
  by (PLM-solver PLM-intro: logic-actual-nec-3[axiom-instance, equiv-rl])
lemma closure-act-4[PLM]:
  [A(∀ α1 α2. A(φ α1 α2) ≡ φ α1 α2) in v]
  by (PLM-solver PLM-intro: logic-actual-nec-3[axiom-instance, equiv-rl])
lemma closure-act-4-b[PLM]:
  [A(∀ α1 α2 α3. A(φ α1 α2 α3) ≡ φ α1 α2 α3) in v]
  by (PLM-solver PLM-intro: logic-actual-nec-3[axiom-instance, equiv-rl])
lemma closure-act-4-c[PLM]:
  [A(∀ α1 α2 α3 α4. A(φ α1 α2 α3 α4) ≡ φ α1 α2 α3 α4) in v]
  by (PLM-solver PLM-intro: logic-actual-nec-3[axiom-instance, equiv-rl])

lemma RA[PLM,PLM-intro]:
  ([φ in dw]) ⇒ [Aφ in dw]
  using logic-actual[necessitation-averse-axiom-instance, equiv-rl] .

lemma RA-2[PLM,PLM-intro]:
  ([ψ in dw] ⇒ [φ in dw]) ⇒ ([Aψ in dw] ⇒ [Aφ in dw])
  using RA logic-actual intro-elim-6-a by blast

context
begin
private lemma ActualE[PLM,PLM-elim,PLM-dest]:
  [Aφ in dw] ⇒ [φ in dw]
  using logic-actual[necessitation-averse-axiom-instance, equiv-lr] .

private lemma NotActualD[PLM-dest]:
  ¬[Aφ in dw] ⇒ ¬[φ in dw]
  using RA by metis

private lemma ActualImplI[PLM-intro]:
  [Aφ → Aψ in v] ⇒ [A(φ → ψ) in v]
  using logic-actual-nec-2[axiom-instance, equiv-rl] .
private lemma ActualImplE[PLM-dest, PLM-elim]:
  [A(φ → ψ) in v] ⇒ [Aφ → Aψ in v]
  using logic-actual-nec-2[axiom-instance, equiv-lr] .
private lemma NotActualImplD[PLM-dest]:
  ¬[A(φ → ψ) in v] ⇒ ¬[Aφ → Aψ in v]
  using ActualImplI by blast

private lemma ActualNotI[PLM-intro]:
  [¬Aφ in v] ⇒ [A¬φ in v]
  using logic-actual-nec-1[axiom-instance, equiv-rl] .
lemma ActualNotE[PLM-elim,PLM-dest]:
  [A¬φ in v] ⇒ [¬Aφ in v]
  using logic-actual-nec-1[axiom-instance, equiv-lr] .
lemma NotActualNotD[PLM-dest]:
  ¬[A¬φ in v] ⇒ ¬[¬Aφ in v]
  using ActualNotI by blast

private lemma ActualConjI[PLM-intro]:
  [Aφ & Aψ in v] ⇒ [A(φ & ψ) in v]

```

```

unfolding equiv-def
by (PLM-solver PLM-intro: act-conj-act-3[deduction])
private lemma ActualConjE[PLM-elim, PLM-dest]:
   $[\mathcal{A}(\varphi \ \& \ \psi) \text{ in } v] \implies [\mathcal{A}\varphi \ \& \ \mathcal{A}\psi \text{ in } v]$ 
unfolding conj-def by PLM-solver

private lemma ActualEquivI[PLM-intro]:
   $[\mathcal{A}\varphi \equiv \mathcal{A}\psi \text{ in } v] \implies [\mathcal{A}(\varphi \equiv \psi) \text{ in } v]$ 
unfolding equiv-def
by (PLM-solver PLM-intro: act-conj-act-3[deduction])
private lemma ActualEquivE[PLM-elim, PLM-dest]:
   $[\mathcal{A}(\varphi \equiv \psi) \text{ in } v] \implies [\mathcal{A}\varphi \equiv \mathcal{A}\psi \text{ in } v]$ 
unfolding equiv-def by PLM-solver

private lemma ActualBoxI[PLM-intro]:
   $[\Box\varphi \text{ in } v] \implies [\mathcal{A}(\Box\varphi) \text{ in } v]$ 
using qml-act-2[axiom-instance, equiv-lr] .
private lemma ActualBoxE[PLM-elim, PLM-dest]:
   $[\mathcal{A}(\Box\varphi) \text{ in } v] \implies [\Box\varphi \text{ in } v]$ 
using qml-act-2[axiom-instance, equiv-rl] .
private lemma NotActualBoxD[PLM-dest]:
   $\neg[\mathcal{A}(\Box\varphi) \text{ in } v] \implies \neg[\Box\varphi \text{ in } v]$ 
using ActualBoxI by blast

private lemma ActualDisjI[PLM-intro]:
   $[\mathcal{A}\varphi \vee \mathcal{A}\psi \text{ in } v] \implies [\mathcal{A}(\varphi \vee \psi) \text{ in } v]$ 
unfolding disj-def by PLM-solver
private lemma ActualDisjE[PLM-elim, PLM-dest]:
   $[\mathcal{A}(\varphi \vee \psi) \text{ in } v] \implies [\mathcal{A}\varphi \vee \mathcal{A}\psi \text{ in } v]$ 
unfolding disj-def by PLM-solver
private lemma NotActualDisjD[PLM-dest]:
   $\neg[\mathcal{A}(\varphi \vee \psi) \text{ in } v] \implies \neg[\mathcal{A}\varphi \vee \mathcal{A}\psi \text{ in } v]$ 
using ActualDisjI by blast

private lemma ActualForallI[PLM-intro]:
   $[\forall x . \mathcal{A}(\varphi x) \text{ in } v] \implies [\mathcal{A}(\forall x . \varphi x) \text{ in } v]$ 
using logic-actual-nec-3[axiom-instance, equiv-rl] .
lemma ActualForallE[PLM-elim, PLM-dest]:
   $[\mathcal{A}(\forall x . \varphi x) \text{ in } v] \implies [\forall x . \mathcal{A}(\varphi x) \text{ in } v]$ 
using logic-actual-nec-3[axiom-instance, equiv-lr] .
lemma NotActualForallD[PLM-dest]:
   $\neg[\mathcal{A}(\forall x . \varphi x) \text{ in } v] \implies \neg[\forall x . \mathcal{A}(\varphi x) \text{ in } v]$ 
using ActualForallI by blast

lemma ActualActualI[PLM-intro]:
   $[\mathcal{A}\varphi \text{ in } v] \implies [\mathcal{A}\mathcal{A}\varphi \text{ in } v]$ 
using logic-actual-nec-4[axiom-instance, equiv-lr] .
lemma ActualActualE[PLM-elim, PLM-dest]:
   $[\mathcal{A}\mathcal{A}\varphi \text{ in } v] \implies [\mathcal{A}\varphi \text{ in } v]$ 
using logic-actual-nec-4[axiom-instance, equiv-rl] .
lemma NotActualActualD[PLM-dest]:
   $\neg[\mathcal{A}\mathcal{A}\varphi \text{ in } v] \implies \neg[\mathcal{A}\varphi \text{ in } v]$ 
using ActualActualI by blast
end

lemma ANeg-1[PLM]:
   $[\neg\mathcal{A}\varphi \equiv \neg\varphi \text{ in } dw]$ 
by PLM-solver
lemma ANeg-2[PLM]:
   $[\neg\mathcal{A}\neg\varphi \equiv \varphi \text{ in } dw]$ 
by PLM-solver
lemma Act-Basic-1[PLM]:
   $[\mathcal{A}\varphi \vee \mathcal{A}\neg\varphi \text{ in } v]$ 

```

by *PLM-solver*
lemma *Act-Basic-2*[*PLM*]:
 $[\mathcal{A}(\varphi \ \& \ \psi) \equiv (\mathcal{A}\varphi \ \& \ \mathcal{A}\psi) \text{ in } v]$
 by *PLM-solver*
lemma *Act-Basic-3*[*PLM*]:
 $[\mathcal{A}(\varphi \equiv \psi) \equiv ((\mathcal{A}(\varphi \rightarrow \psi)) \ \& \ (\mathcal{A}(\psi \rightarrow \varphi))) \text{ in } v]$
 by *PLM-solver*
lemma *Act-Basic-4*[*PLM*]:
 $[(\mathcal{A}(\varphi \rightarrow \psi) \ \& \ \mathcal{A}(\psi \rightarrow \varphi)) \equiv (\mathcal{A}\varphi \equiv \mathcal{A}\psi) \text{ in } v]$
 by *PLM-solver*
lemma *Act-Basic-5*[*PLM*]:
 $[\mathcal{A}(\varphi \equiv \psi) \equiv (\mathcal{A}\varphi \equiv \mathcal{A}\psi) \text{ in } v]$
 by *PLM-solver*
lemma *Act-Basic-6*[*PLM*]:
 $[\Diamond\varphi \equiv \mathcal{A}(\Diamond\varphi) \text{ in } v]$
 unfolding *diamond-def* by *PLM-solver*
lemma *Act-Basic-7*[*PLM*]:
 $[\mathcal{A}\varphi \equiv \Box\mathcal{A}\varphi \text{ in } v]$
 by (*simp add: qml-2[axiom-instance] qml-act-1[axiom-instance] $\equiv I$*)
lemma *Act-Basic-8*[*PLM*]:
 $[\mathcal{A}(\Box\varphi) \rightarrow \Box\mathcal{A}\varphi \text{ in } v]$
 by (*metis qml-act-2[axiom-instance] CP Act-Basic-7 $\equiv E(1)$
 $\equiv E(2)$ nec-imp-act vdash-properties-10*)
lemma *Act-Basic-9*[*PLM*]:
 $[\Box\varphi \rightarrow \Box\mathcal{A}\varphi \text{ in } v]$
 using *qml-act-1[axiom-instance] ded-thm-cor-3 nec-imp-act* by *blast*
lemma *Act-Basic-10*[*PLM*]:
 $[\mathcal{A}(\varphi \vee \psi) \equiv \mathcal{A}\varphi \vee \mathcal{A}\psi \text{ in } v]$
 by *PLM-solver*

lemma *Act-Basic-11*[*PLM*]:
 $[\mathcal{A}(\exists \alpha. \varphi \ \alpha) \equiv (\exists \alpha. \mathcal{A}(\varphi \ \alpha)) \text{ in } v]$
proof –
 have $[\mathcal{A}(\forall \alpha. \neg \varphi \ \alpha) \equiv (\forall \alpha. \mathcal{A}\neg \varphi \ \alpha) \text{ in } v]$
 using *logic-actual-nec-3[axiom-instance]* by *blast*
 hence $[\neg \mathcal{A}(\forall \alpha. \neg \varphi \ \alpha) \equiv \neg(\forall \alpha. \mathcal{A}\neg \varphi \ \alpha) \text{ in } v]$
 using *oth-class-taut-5-d[equiv-lr]* by *blast*
 moreover have $[\mathcal{A}\neg(\forall \alpha. \neg \varphi \ \alpha) \equiv \neg \mathcal{A}(\forall \alpha. \neg \varphi \ \alpha) \text{ in } v]$
 using *logic-actual-nec-1[axiom-instance]* by *blast*
 ultimately have $[\mathcal{A}\neg(\forall \alpha. \neg \varphi \ \alpha) \equiv \neg(\forall \alpha. \mathcal{A}\neg \varphi \ \alpha) \text{ in } v]$
 using $\equiv E(5)$ by *auto*
 moreover {
 have $[\forall \alpha. \mathcal{A}\neg \varphi \ \alpha \equiv \neg \mathcal{A}\varphi \ \alpha \text{ in } v]$
 using *logic-actual-nec-1[axiom-universal, axiom-instance]* by *blast*
 hence $[(\forall \alpha. \mathcal{A}\neg \varphi \ \alpha) \equiv (\forall \alpha. \neg \mathcal{A}\varphi \ \alpha) \text{ in } v]$
 using *cqt-basic-3[deduction]* by *fast*
 hence $[(\neg(\forall \alpha. \mathcal{A}\neg \varphi \ \alpha)) \equiv \neg(\forall \alpha. \neg \mathcal{A}\varphi \ \alpha) \text{ in } v]$
 using *oth-class-taut-5-d[equiv-lr]* by *blast*
 }
 ultimately show *?thesis* unfolding *exists-def* using $\equiv E(5)$ by *auto*
 qed

lemma *act-quant-uniq*[*PLM*]:
 $[(\forall z. \mathcal{A}\varphi \ z \equiv z = x) \equiv (\forall z. \varphi \ z \equiv z = x) \text{ in } dw]$
 by *PLM-solver*

lemma *fund-cont-desc*[*PLM*]:
 $[(x^P = (\iota x. \varphi \ x)) \equiv (\forall z. \varphi \ z \equiv (z = x)) \text{ in } dw]$
 using *descriptions[axiom-instance] act-quant-uniq $\equiv E(5)$* by *fast*

lemma *hintikka*[*PLM*]:
 $[(x^P = (\iota x. \varphi \ x)) \equiv (\varphi \ x \ \& \ (\forall z. \varphi \ z \rightarrow z = x)) \text{ in } dw]$
proof –


```

using 1 l-identity[where  $\beta=\alpha^P$  and  $\alpha=\iota x. \varphi x$  and  $\varphi=\lambda x. \llbracket x, F \rrbracket$ ,
                    axiom-instance, deduction, deduction] by auto
with 3 have  $[(\varphi \alpha \ \& \ (\forall z. \varphi z \rightarrow z = \alpha)) \ \& \ \llbracket \alpha^P, F \rrbracket \text{ in } dw]$ 
  using &I by auto
hence  $[?rhs \text{ in } dw]$  using  $\exists I$ [where  $\alpha=\alpha$ ] by (simp add: identity-defs)
}
moreover {
  assume  $[?rhs \text{ in } dw]$ 
  then obtain  $\alpha$  where 4:
     $[\varphi \alpha \ \& \ (\forall z. \varphi z \rightarrow z = \alpha) \ \& \ \llbracket \alpha^P, F \rrbracket \text{ in } dw]$ 
    using  $\exists E$  by auto
  hence  $[\alpha^P = (\iota x. \varphi x) \text{ in } dw] \wedge [\llbracket \alpha^P, F \rrbracket \text{ in } dw]$ 
    using hintikka[equiv-rl] &E by blast
  hence  $[?lhs \text{ in } dw]$ 
    using l-identity[axiom-instance, deduction, deduction]
    by fast
}
ultimately show ?thesis by PLM-solver
qed

```

lemma russell-axiom[PLM]:

```

assumes SimpleExOrEnc  $\psi$ 
shows  $[\psi (\iota x. \varphi x) \equiv (\exists x. \varphi x \ \& \ (\forall z. \varphi z \rightarrow z = x) \ \& \ \psi (x^P)) \text{ in } dw]$ 
(is  $[?lhs \equiv ?rhs \text{ in } dw]$ )
proof -
{
  assume 1:  $[?lhs \text{ in } dw]$ 
  hence  $[\exists \alpha. \alpha^P = (\iota x. \varphi x) \text{ in } dw]$ 
  using cqt-5[axiom-instance, deduction] assms by blast
  then obtain  $\alpha$  where 2:  $[\alpha^P = (\iota x. \varphi x) \text{ in } dw]$  by (rule  $\exists E$ )
  hence 3:  $[(\varphi \alpha \ \& \ (\forall z. \varphi z \rightarrow z = \alpha)) \text{ in } dw]$ 
    using hintikka[equiv-lr] by simp
  from 2 have  $[(\iota x. \varphi x) = (\alpha^P) \text{ in } dw]$ 
    using l-identity[where  $\alpha=\alpha^P$  and  $\beta=\iota x. \varphi x$  and  $\varphi=\lambda x. x = \alpha^P$ ,
                    axiom-instance, deduction, deduction]
    id-eq-obj-1[where  $x=\alpha$ ] by auto
  hence  $[\psi (\alpha^P) \text{ in } dw]$ 
    using 1 l-identity[where  $\beta=\alpha^P$  and  $\alpha=\iota x. \varphi x$  and  $\varphi=\lambda x. \psi x$ ,
                    axiom-instance, deduction, deduction] by auto
  with 3 have  $[\varphi \alpha \ \& \ (\forall z. \varphi z \rightarrow z = \alpha) \ \& \ \psi (\alpha^P) \text{ in } dw]$ 
    using &I by auto
  hence  $[?rhs \text{ in } dw]$  using  $\exists I$ [where  $\alpha=\alpha$ ] by (simp add: identity-defs)
}
moreover {
  assume  $[?rhs \text{ in } dw]$ 
  then obtain  $\alpha$  where 4:
     $[\varphi \alpha \ \& \ (\forall z. \varphi z \rightarrow z = \alpha) \ \& \ \psi (\alpha^P) \text{ in } dw]$ 
    using  $\exists E$  by auto
  hence  $[\alpha^P = (\iota x. \varphi x) \text{ in } dw] \wedge [\psi (\alpha^P) \text{ in } dw]$ 
    using hintikka[equiv-rl] &E by blast
  hence  $[?lhs \text{ in } dw]$ 
    using l-identity[axiom-instance, deduction, deduction]
    by fast
}
ultimately show ?thesis by PLM-solver
qed

```

lemma unique-exists[PLM]:

```

 $[(\exists y. y^P = (\iota x. \varphi x)) \equiv (\exists !x. \varphi x) \text{ in } dw]$ 
proof((rule  $\equiv I$ , rule CP, rule-tac[2] CP))
  assume  $[\exists y. y^P = (\iota x. \varphi x) \text{ in } dw]$ 
  then obtain  $\alpha$  where
     $[\alpha^P = (\iota x. \varphi x) \text{ in } dw]$ 

```

```

    by (rule  $\exists E$ )
  hence  $[\varphi \alpha \ \& \ (\forall \beta. \varphi \beta \rightarrow \beta = \alpha) \text{ in } dw]$ 
    using hintikka[equiv-lr] by auto
  thus  $[\exists !x. \varphi x \text{ in } dw]$ 
    unfolding exists-unique-def using  $\exists I$  by fast
next
  assume  $[\exists !x. \varphi x \text{ in } dw]$ 
  then obtain  $\alpha$  where
     $[\varphi \alpha \ \& \ (\forall \beta. \varphi \beta \rightarrow \beta = \alpha) \text{ in } dw]$ 
    unfolding exists-unique-def by (rule  $\exists E$ )
  hence  $[\alpha^P = (\iota x. \varphi x) \text{ in } dw]$ 
    using hintikka[equiv-rl] by auto
  thus  $[\exists y. y^P = (\iota x. \varphi x) \text{ in } dw]$ 
    using  $\exists I$  by fast
qed

lemma y-in-1[PLM]:
 $[x^P = (\iota x. \varphi) \rightarrow \varphi \text{ in } dw]$ 
  using hintikka[equiv-lr, conj1] by (rule CP)

lemma y-in-2[PLM]:
 $[z^P = (\iota x. \varphi x) \rightarrow \varphi z \text{ in } dw]$ 
  using hintikka[equiv-lr, conj1] by (rule CP)

lemma y-in-3[PLM]:
 $[(\exists y. y^P = (\iota x. \varphi (x^P))) \rightarrow \varphi (\iota x. \varphi (x^P)) \text{ in } dw]$ 
  proof (rule CP)
    assume  $[(\exists y. y^P = (\iota x. \varphi (x^P))) \text{ in } dw]$ 
    then obtain  $y$  where 1:
       $[y^P = (\iota x. \varphi (x^P)) \text{ in } dw]$ 
      by (rule  $\exists E$ )
    hence  $[\varphi (y^P) \text{ in } dw]$ 
      using y-in-2[deduction] unfolding identity- $\nu$ -def by blast
    thus  $[\varphi (\iota x. \varphi (x^P)) \text{ in } dw]$ 
      using l-identity[axiom-instance, deduction, deduction] 1 by fast
  qed

lemma act-quant-nec[PLM]:
 $[(\forall z. (\mathcal{A}\varphi z \equiv z = x)) \equiv (\forall z. \mathcal{A}\mathcal{A}\varphi z \equiv z = x) \text{ in } v]$ 
  by PLM-solver

lemma equi-desc-descA-1[PLM]:
 $[(x^P = (\iota x. \varphi x)) \equiv (x^P = (\iota x. \mathcal{A}\varphi x)) \text{ in } v]$ 
  using descriptions[axiom-instance] apply (rule  $\equiv E(5)$ )
  using act-quant-nec apply (rule  $\equiv E(5)$ )
  using descriptions[axiom-instance]
  by (meson  $\equiv E(6)$  oth-class-taut-4-a)

lemma equi-desc-descA-2[PLM]:
 $[(\exists y. y^P = (\iota x. \varphi x)) \rightarrow ((\iota x. \varphi x) = (\iota x. \mathcal{A}\varphi x)) \text{ in } v]$ 
  proof (rule CP)
    assume  $[\exists y. y^P = (\iota x. \varphi x) \text{ in } v]$ 
    then obtain  $y$  where
       $[y^P = (\iota x. \varphi x) \text{ in } v]$ 
      by (rule  $\exists E$ )
    moreover hence  $[y^P = (\iota x. \mathcal{A}\varphi x) \text{ in } v]$ 
      using equi-desc-descA-1[equiv-lr] by auto
    ultimately show  $[(\iota x. \varphi x) = (\iota x. \mathcal{A}\varphi x) \text{ in } v]$ 
      using l-identity[axiom-instance, deduction, deduction]
      by fast
  qed

```

lemma *equi-desc-descA-3*[PLM]:
assumes *SimpleExOrEnc* ψ
shows $[\psi (\iota x. \varphi x) \rightarrow (\exists y. y^P = (\iota x. \mathcal{A}\varphi x)) \text{ in } v]$
proof (*rule CP*)
 assume $[\psi (\iota x. \varphi x) \text{ in } v]$
 hence $[\exists \alpha. \alpha^P = (\iota x. \varphi x) \text{ in } v]$
 using *cqt-5*[*OF assms, axiom-instance, deduction*] **by** *auto*
 then obtain α **where** $[\alpha^P = (\iota x. \varphi x) \text{ in } v]$ **by** (*rule* $\exists E$)
 hence $[\alpha^P = (\iota x. \mathcal{A}\varphi x) \text{ in } v]$
 using *equi-desc-descA-1*[*equiv-lr*] **by** *auto*
 thus $[\exists y. y^P = (\iota x. \mathcal{A}\varphi x) \text{ in } v]$
 using $\exists I$ **by** *fast*
qed

lemma *equi-desc-descA-4*[PLM]:
assumes *SimpleExOrEnc* ψ
shows $[\psi (\iota x. \varphi x) \rightarrow ((\iota x. \varphi x) = (\iota x. \mathcal{A}\varphi x)) \text{ in } v]$
proof (*rule CP*)
 assume $[\psi (\iota x. \varphi x) \text{ in } v]$
 hence $[\exists \alpha. \alpha^P = (\iota x. \varphi x) \text{ in } v]$
 using *cqt-5*[*OF assms, axiom-instance, deduction*] **by** *auto*
 then obtain α **where** $[\alpha^P = (\iota x. \varphi x) \text{ in } v]$ **by** (*rule* $\exists E$)
 moreover hence $[\alpha^P = (\iota x. \mathcal{A}\varphi x) \text{ in } v]$
 using *equi-desc-descA-1*[*equiv-lr*] **by** *auto*
 ultimately show $[(\iota x. \varphi x) = (\iota x. \mathcal{A}\varphi x) \text{ in } v]$
 using *l-identity*[*axiom-instance, deduction, deduction*] **by** *fast*
qed

lemma *nec-hintikka-scheme*[PLM]:
 $[(x^P = (\iota x. \varphi x)) \equiv (\mathcal{A}\varphi x \ \& \ (\forall z. \mathcal{A}\varphi z \rightarrow z = x)) \text{ in } v]$
using *descriptions*[*axiom-instance*]
apply (*rule* $\equiv E(5)$)
apply *PLM-solver*
 using *id-eq-obj-1* **apply** *simp*
 using *id-eq-obj-2*[*deduction*]
 l-identity[**where** $\alpha=x$, *axiom-instance, deduction, deduction*]
 unfolding *identity- ν -def*
 apply *blast*
using *l-identity*[**where** $\alpha=x$, *axiom-instance, deduction, deduction*]
id-eq-2[**where** $a=\nu$, *deduction*] **unfolding** *identity- ν -def* **by** *meson*

lemma *equiv-desc-eq*[PLM]:
assumes $\bigwedge x. [\mathcal{A}(\varphi x \equiv \psi x) \text{ in } v]$
shows $[(\forall x. ((x^P = (\iota x. \varphi x)) \equiv (x^P = (\iota x. \psi x)))) \text{ in } v]$
proof(*rule* $\forall I$)
 fix x
 {
 assume $[x^P = (\iota x. \varphi x) \text{ in } v]$
 hence $1: [\mathcal{A}\varphi x \ \& \ (\forall z. \mathcal{A}\varphi z \rightarrow z = x) \text{ in } v]$
 using *nec-hintikka-scheme*[*equiv-lr*] **by** *auto*
 hence $2: [\mathcal{A}\varphi x \text{ in } v] \wedge [(\forall z. \mathcal{A}\varphi z \rightarrow z = x) \text{ in } v]$
 using $\&E$ **by** *blast*
 {
 fix z
 {
 assume $[\mathcal{A}\psi z \text{ in } v]$
 hence $[\mathcal{A}\varphi z \text{ in } v]$
 using *assms*[**where** $x=z$] **apply** *cut-tac* **by** *PLM-solver*
 moreover have $[\mathcal{A}\varphi z \rightarrow z = x \text{ in } v]$
 using *2 cqt-1*[*axiom-instance, deduction*] **by** *auto*
 ultimately have $[z = x \text{ in } v]$
 using *vdash-properties-10* **by** *auto*
 }
 }
 }


```

    hence [ $\mathcal{A}\psi z \rightarrow z = x$  in  $v$ ] by (rule CP)
  }
  hence [ $(\forall z . \mathcal{A}\psi z \rightarrow z = x)$  in  $v$ ] by (rule  $\forall I$ )
  moreover have [ $\mathcal{A}\psi x$  in  $v$ ]
    using 1[conj1] assms[where  $x=x$ ]
    apply cut-tac by PLM-solver
  ultimately have [ $\mathcal{A}\psi x \ \& \ (\forall z. \mathcal{A}\psi z \rightarrow z = x)$  in  $v$ ]
    by PLM-solver
  hence [ $x^P = (\iota x. \psi x)$  in  $v$ ]
    using nec-hintikka-scheme[where  $\varphi=\psi$ , equiv-rl] by auto
}
moreover {
  assume [ $x^P = (\iota x. \psi x)$  in  $v$ ]
  hence 1: [ $\mathcal{A}\psi x \ \& \ (\forall z. \mathcal{A}\psi z \rightarrow z = x)$  in  $v$ ]
    using nec-hintikka-scheme[equiv-lr] by auto
  hence 2: [ $\mathcal{A}\psi x$  in  $v$ ]  $\wedge$  [ $(\forall z. \mathcal{A}\psi z \rightarrow z = x)$  in  $v$ ]
    using &E by blast
  {
    fix z
    {
      assume [ $\mathcal{A}\varphi z$  in  $v$ ]
      hence [ $\mathcal{A}\psi z$  in  $v$ ]
        using assms[where  $x=z$ ]
        apply cut-tac by PLM-solver
      moreover have [ $\mathcal{A}\psi z \rightarrow z = x$  in  $v$ ]
        using 2 cqt-1[axiom-instance,deduction] by auto
      ultimately have [ $z = x$  in  $v$ ]
        using vdash-properties-10 by auto
    }
    hence [ $\mathcal{A}\varphi z \rightarrow z = x$  in  $v$ ] by (rule CP)
  }
}
  hence [ $(\forall z. \mathcal{A}\varphi z \rightarrow z = x)$  in  $v$ ] by (rule  $\forall I$ )
  moreover have [ $\mathcal{A}\varphi x$  in  $v$ ]
    using 1[conj1] assms[where  $x=x$ ]
    apply cut-tac by PLM-solver
  ultimately have [ $\mathcal{A}\varphi x \ \& \ (\forall z. \mathcal{A}\varphi z \rightarrow z = x)$  in  $v$ ]
    by PLM-solver
  hence [ $x^P = (\iota x. \varphi x)$  in  $v$ ]
    using nec-hintikka-scheme[where  $\varphi=\varphi$ ,equiv-rl]
    by auto
}
ultimately show [ $x^P = (\iota x. \varphi x) \equiv (x^P) = (\iota x. \psi x)$  in  $v$ ]
  using  $\equiv I$  CP by auto
qed

```

lemma UniqueAux:

```

assumes [( $\mathcal{A}\varphi (\alpha::\nu) \ \& \ (\forall z . \mathcal{A}(\varphi z) \rightarrow z = \alpha)$ ) in  $v$ ]
shows [( $\forall z . (\mathcal{A}(\varphi z) \equiv (z = \alpha))$ ) in  $v$ ]
proof -
  {
    fix z
    {
      assume [ $\mathcal{A}(\varphi z)$  in  $v$ ]
      hence [ $z = \alpha$  in  $v$ ]
        using assms[conj2, THEN cqt-1[where  $\alpha=z$ ,
          axiom-instance, deduction],
          deduction] by auto
    }
  }
  moreover {
    assume [ $z = \alpha$  in  $v$ ]
    hence [ $\alpha = z$  in  $v$ ]
      unfolding identity- $\nu$ -def
      using id-eq-obj-2[deduction] by fast
  }

```

```

    hence  $[\mathcal{A}(\varphi z) \text{ in } v]$  using assms[conj1]
      using l-identity[axiom-instance, deduction,
        deduction] by fast
  }
  ultimately have  $[(\mathcal{A}(\varphi z) \equiv (z = \alpha)) \text{ in } v]$ 
    using  $\equiv I$  CP by auto
}
thus  $[(\forall z . (\mathcal{A}(\varphi z) \equiv (z = \alpha))) \text{ in } v]$ 
  by (rule  $\forall I$ )
qed

```

lemma *nec-russell-axiom[PLM]*:

```

  assumes SimpleExOrEnc  $\psi$ 
  shows  $[(\psi (\iota x. \varphi x)) \equiv (\exists x . (\mathcal{A}\varphi x \ \& \ (\forall z . \mathcal{A}(\varphi z) \rightarrow z = x))$ 
     $\& \ \psi (\alpha^P)) \text{ in } v]$ 
  (is  $[\text{?lhs} \equiv \text{?rhs} \text{ in } v]$ )
  proof -
  {
    assume 1:  $[\text{?lhs} \text{ in } v]$ 
    hence  $[\exists \alpha. (\alpha^P) = (\iota x. \varphi x) \text{ in } v]$ 
      using cqt-5[axiom-instance, deduction] assms by blast
    then obtain  $\alpha$  where 2:  $[(\alpha^P) = (\iota x. \varphi x) \text{ in } v]$  by (rule  $\exists E$ )
    hence  $[(\forall z . (\mathcal{A}(\varphi z) \equiv (z = \alpha))) \text{ in } v]$ 
      using descriptions[axiom-instance, equiv-lr] by auto
    hence 3:  $[(\mathcal{A}\varphi \alpha \ \& \ (\forall z . (\mathcal{A}(\varphi z) \rightarrow (z = \alpha)))) \text{ in } v]$ 
      using cqt-1[where  $\alpha=\alpha$  and  $\varphi=\lambda z . (\mathcal{A}(\varphi z) \equiv (z = \alpha))$ ,
        axiom-instance, deduction, equiv-rl]
      using id-eq-obj-1[where  $x=\alpha$ ] unfolding identity- $\nu$ -def
      using hintikka[equiv-lr] cqt-basic-2[equiv-lr, conj1]
      & I by fast
    from 2 have  $[(\iota x. \varphi x) = (\alpha^P) \text{ in } v]$ 
      using l-identity[where  $\beta=(\iota x. \varphi x)$  and  $\varphi=\lambda x . x = (\alpha^P)$ ,
        axiom-instance, deduction, deduction]
      id-eq-obj-1[where  $x=\alpha$ ] by auto
    hence  $[\psi (\alpha^P) \text{ in } v]$ 
      using 1 l-identity[where  $\alpha=(\iota x. \varphi x)$  and  $\varphi=\lambda x . \psi x$ ,
        axiom-instance, deduction,
        deduction] by auto
    with 3 have  $[(\mathcal{A}\varphi \alpha \ \& \ (\forall z . \mathcal{A}(\varphi z) \rightarrow (z = \alpha))) \ \& \ \psi (\alpha^P) \text{ in } v]$ 
      using &I by simp
    hence  $[\text{?rhs} \text{ in } v]$ 
      using  $\exists I$  [where  $\alpha=\alpha$ ]
      by (simp add: identity-defs)
  }
  moreover {
    assume  $[\text{?rhs} \text{ in } v]$ 
    then obtain  $\alpha$  where 4:
       $[(\mathcal{A}\varphi \alpha \ \& \ (\forall z . \mathcal{A}(\varphi z) \rightarrow z = \alpha)) \ \& \ \psi (\alpha^P) \text{ in } v]$ 
      using  $\exists E$  by auto
    hence  $[(\forall z . (\mathcal{A}(\varphi z) \equiv (z = \alpha))) \text{ in } v]$ 
      using UniqueAux &E(1) by auto
    hence  $[(\alpha^P) = (\iota x . \varphi x) \text{ in } v] \wedge [\psi (\alpha^P) \text{ in } v]$ 
      using descriptions[axiom-instance, equiv-rl]
      4 [conj2] by blast
    hence  $[\text{?lhs} \text{ in } v]$ 
      using l-identity[axiom-instance, deduction,
        deduction]
      by fast
  }
  ultimately show ?thesis by PLM-solver
qed

```

lemma *actual-desc-1[PLM]*:

```

[( $\exists y . (y^P) = (\iota x . \varphi x)$ )  $\equiv$  ( $\exists ! x . \mathcal{A}(\varphi x)$ ) in  $v$ ] (is [ $?lhs \equiv ?rhs$  in  $v$ ])
proof –
{
  assume [ $?lhs$  in  $v$ ]
  then obtain  $\alpha$  where
    [( $\alpha^P = (\iota x . \varphi x)$ ) in  $v$ ]
    by (rule  $\exists E$ )
  hence [( $\lambda !, (\iota x . \varphi x) \lambda$ ) in  $v$ ]  $\vee$  [( $\alpha^P =_E (\iota x . \varphi x)$ ) in  $v$ ]
  apply (cut-tac) unfolding identity-defs by PLM-solver
  then obtain  $x$  where
    [( $(\mathcal{A}\varphi x \ \& \ (\forall z . \mathcal{A}(\varphi z) \rightarrow z = x))$ ) in  $v$ ]
    using nec-russell-axiom[where  $\psi = \lambda x . (\lambda !, x)$ , equiv-lr, THEN  $\exists E$ ]
    using nec-russell-axiom[where  $\psi = \lambda x . (\alpha^P) =_E x$ , equiv-lr, THEN  $\exists E$ ]
    using SimpleExOrEnc.intros unfolding identityE-infix-def
    by (meson &E)
  hence [ $?rhs$  in  $v$ ] unfolding exists-unique-def by (rule  $\exists I$ )
}
moreover {
  assume [ $?rhs$  in  $v$ ]
  then obtain  $x$  where
    [( $(\mathcal{A}\varphi x \ \& \ (\forall z . \mathcal{A}(\varphi z) \rightarrow z = x))$ ) in  $v$ ]
    unfolding exists-unique-def by (rule  $\exists E$ )
  hence [ $\forall z . \mathcal{A}\varphi z \equiv z = x$  in  $v$ ]
    using UniqueAux by auto
  hence [( $x^P = (\iota x . \varphi x)$ ) in  $v$ ]
    using descriptions[axiom-instance, equiv-rl] by auto
  hence [ $?lhs$  in  $v$ ] by (rule  $\exists I$ )
}
ultimately show ?thesis
using  $\equiv I$  CP by auto
qed

```

lemma actual-desc-2[PLM]:
 [($x^P = (\iota x . \varphi) \rightarrow \mathcal{A}\varphi$) in v]
using nec-hintikka-scheme[equiv-lr, conj1]
by (rule CP)

lemma actual-desc-3[PLM]:
 [($z^P = (\iota x . \varphi x) \rightarrow \mathcal{A}(\varphi z)$) in v]
using nec-hintikka-scheme[equiv-lr, conj1]
by (rule CP)

lemma actual-desc-4[PLM]:
 [($\exists y . ((y^P) = (\iota x . \varphi (x^P))) \rightarrow \mathcal{A}(\varphi (\iota x . \varphi (x^P)))$) in v]
proof (rule CP)
assume [($\exists y . (y^P) = (\iota x . \varphi (x^P))$) in v]
then obtain y **where** 1:
 [$y^P = (\iota x . \varphi (x^P))$ in v]
by (rule $\exists E$)
hence [$\mathcal{A}(\varphi (y^P))$ in v] **using** actual-desc-3[deduction] **by** fast
thus [$\mathcal{A}(\varphi (\iota x . \varphi (x^P)))$ in v]
using l-identity[axiom-instance, deduction,
 deduction] 1 **by** fast

qed

lemma unique-box-desc-1[PLM]:
 [($\exists ! x . \Box(\varphi x) \rightarrow (\forall y . (y^P) = (\iota x . \varphi x) \rightarrow \varphi y)$) in v]
proof (rule CP)
assume [($\exists ! x . \Box(\varphi x)$) in v]
then obtain α **where** 1:
 [$\Box\varphi \ \& \ (\forall \beta . \Box(\varphi \beta) \rightarrow \beta = \alpha)$ in v]
unfolding exists-unique-def **by** (rule $\exists E$)
 {

```

fix y
{
  assume [(yP) = (λx. φ x) in v]
  hence [Aφ α → α = y in v]
    using nec-hintikka-scheme[where x=y and φ=φ, equiv-lr, conj2,
      THEN cqt-1[where α=α, axiom-instance, deduction]] by simp
  hence [α = y in v]
    using 1[conj1] nec-imp-act vdash-properties-10 by blast
  hence [φ y in v]
    using 1[conj1] qml-2[axiom-instance, deduction]
      l-identity[axiom-instance, deduction, deduction]
    by fast
}
hence [(yP) = (λx. φ x) → φ y in v]
  by (rule CP)
}
thus [∀ y . (yP) = (λx. φ x) → φ y in v]
  by (rule ∀ I)
qed

```

lemma *unique-box-desc[PLM]*:

$$[(\forall x . (\varphi x \rightarrow \Box(\varphi x))) \rightarrow ((\exists !x . \varphi x) \rightarrow (\forall y . (y^P = (\lambda x . \varphi x)) \rightarrow \varphi y)) \text{ in } v]$$

apply (rule CP, rule CP)
using nec-exist-unique[deduction, deduction]
 unique-box-desc-1[deduction] **by** blast

9.10 Necessity

lemma *RM-1[PLM]*:

$$(\bigwedge v. [\varphi \rightarrow \psi \text{ in } v]) \implies [\Box \varphi \rightarrow \Box \psi \text{ in } v]$$

using RN qml-1[axiom-instance] vdash-properties-10 **by** blast

lemma *RM-1-b[PLM]*:

$$(\bigwedge v. [\chi \text{ in } v] \implies [\varphi \rightarrow \psi \text{ in } v]) \implies ([\Box \chi \text{ in } v] \implies [\Box \varphi \rightarrow \Box \psi \text{ in } v])$$

using RN-2 qml-1[axiom-instance] vdash-properties-10 **by** blast

lemma *RM-2[PLM]*:

$$(\bigwedge v. [\varphi \rightarrow \psi \text{ in } v]) \implies [\Diamond \varphi \rightarrow \Diamond \psi \text{ in } v]$$

unfolding diamond-def
using RM-1 contraposition-1 **by** auto

lemma *RM-2-b[PLM]*:

$$(\bigwedge v. [\chi \text{ in } v] \implies [\varphi \rightarrow \psi \text{ in } v]) \implies ([\Box \chi \text{ in } v] \implies [\Diamond \varphi \rightarrow \Diamond \psi \text{ in } v])$$

unfolding diamond-def
using RM-1-b contraposition-1 **by** blast

lemma *KBasic-1[PLM]*:

$$[\Box \varphi \rightarrow \Box(\psi \rightarrow \varphi) \text{ in } v]$$

by (simp only: pl-1[axiom-instance] RM-1)

lemma *KBasic-2[PLM]*:

$$[\Box(\neg \varphi) \rightarrow \Box(\varphi \rightarrow \psi) \text{ in } v]$$

by (simp only: RM-1 useful-tautologies-3)

lemma *KBasic-3[PLM]*:

$$[\Box(\varphi \ \& \ \psi) \equiv \Box \varphi \ \& \ \Box \psi \text{ in } v]$$

apply (rule ≡I)
apply (rule CP)
apply (rule &I)
 using RM-1 oth-class-taut-9-a vdash-properties-6 **apply** blast
 using RM-1 oth-class-taut-9-b vdash-properties-6 **apply** blast
using qml-1[axiom-instance] RM-1 ded-thm-cor-3 oth-class-taut-10-a oth-class-taut-8-b
 vdash-properties-10
by blast

lemma *KBasic-4*[*PLM*]:
 $[(\Box(\varphi \equiv \psi) \equiv (\Box(\varphi \rightarrow \psi) \ \& \ \Box(\psi \rightarrow \varphi))) \text{ in } v]$
apply (*rule* $\equiv I$)
unfolding *equiv-def* **using** *KBasic-3* *PLM.CP* $\equiv E(1)$
apply *blast*
using *KBasic-3* *PLM.CP* $\equiv E(2)$
by *blast*

lemma *KBasic-5*[*PLM*]:
 $[(\Box(\varphi \rightarrow \psi) \ \& \ \Box(\psi \rightarrow \varphi)) \rightarrow (\Box\varphi \equiv \Box\psi) \text{ in } v]$
by (*metis* *qml-1*[*axiom-instance*] *CP* $\&E$ $\equiv I$ *vdash-properties-10*)

lemma *KBasic-6*[*PLM*]:
 $[(\Box(\varphi \equiv \psi) \rightarrow (\Box\varphi \equiv \Box\psi)) \text{ in } v]$
using *KBasic-4* *KBasic-5* **by** (*metis* *equiv-def* *ded-thm-cor-3* $\&E(1)$)

lemma $[(\Box\varphi \equiv \Box\psi) \rightarrow \Box(\varphi \equiv \psi) \text{ in } v]$
nitpick[*expect=genuine, user-axioms, card = 1, card i = 2*]
oops — countermodel as desired

lemma *KBasic-7*[*PLM*]:
 $[(\Box\varphi \ \& \ \Box\psi) \rightarrow \Box(\varphi \equiv \psi) \text{ in } v]$
proof (*rule* *CP*)
assume $[\Box\varphi \ \& \ \Box\psi \text{ in } v]$
hence $[\Box(\psi \rightarrow \varphi) \text{ in } v] \wedge [\Box(\varphi \rightarrow \psi) \text{ in } v]$
using $\&E$ *KBasic-1* *vdash-properties-10* **by** *blast*
thus $[\Box(\varphi \equiv \psi) \text{ in } v]$
using *KBasic-4* $\equiv E(2)$ *intro-elim-1* **by** *blast*
qed

lemma *KBasic-8*[*PLM*]:
 $[(\Box(\varphi \ \& \ \psi) \rightarrow \Box(\varphi \equiv \psi)) \text{ in } v]$
using *KBasic-7* *KBasic-3*
by (*metis* *equiv-def* *PLM.ded-thm-cor-3* $\&E(1)$)

lemma *KBasic-9*[*PLM*]:
 $[(\Box((\neg\varphi) \ \& \ (\neg\psi)) \rightarrow \Box(\varphi \equiv \psi)) \text{ in } v]$
proof (*rule* *CP*)
assume $[\Box((\neg\varphi) \ \& \ (\neg\psi)) \text{ in } v]$
hence $[\Box((\neg\varphi) \equiv (\neg\psi)) \text{ in } v]$
using *KBasic-8* *vdash-properties-10* **by** *blast*
moreover **have** $\bigwedge v. [((\neg\varphi) \equiv (\neg\psi)) \rightarrow (\varphi \equiv \psi) \text{ in } v]$
using *CP* $\equiv E(2)$ *oth-class-taut-5-d* **by** *blast*
ultimately **show** $[\Box(\varphi \equiv \psi) \text{ in } v]$
using *RM-1* *PLM.vdash-properties-10* **by** *blast*
qed

lemma *rule-sub-lem-1-a*[*PLM*]:
 $[(\Box(\psi \equiv \chi) \text{ in } v) \implies [(\neg\psi) \equiv (\neg\chi) \text{ in } v]]$
using *qml-2*[*axiom-instance*] $\equiv E(1)$ *oth-class-taut-5-d*
vdash-properties-10
by *blast*

lemma *rule-sub-lem-1-b*[*PLM*]:
 $[(\Box(\psi \equiv \chi) \text{ in } v) \implies [(\psi \rightarrow \Theta) \equiv (\chi \rightarrow \Theta) \text{ in } v]]$
by (*metis* *equiv-def* *contraposition-1* *CP* $\&E(2)$ $\equiv I$ $\equiv E(1)$ *rule-sub-lem-1-a*)

lemma *rule-sub-lem-1-c*[*PLM*]:
 $[(\Box(\psi \equiv \chi) \text{ in } v) \implies [(\Theta \rightarrow \psi) \equiv (\Theta \rightarrow \chi) \text{ in } v]]$
by (*metis* *CP* $\equiv I$ $\equiv E(3)$ $\equiv E(4)$ $\neg\neg I$ $\neg\neg E$ *rule-sub-lem-1-a*)

lemma *rule-sub-lem-1-d*[*PLM*]:
 $(\bigwedge x. [\Box(\psi \equiv \chi \ x) \text{ in } v]) \implies [(\forall \alpha. \psi \ \alpha) \equiv (\forall \alpha. \chi \ \alpha) \text{ in } v]$
by (*metis* *equiv-def* $\forall I$ *CP* $\&E$ $\equiv I$ *raa-cor-1* *vdash-properties-10* *rule-sub-lem-1-a* $\forall E$)

lemma *rule-sub-lem-1-e*[*PLM*]:
 $[(\Box(\psi \equiv \chi) \text{ in } v) \implies [\mathcal{A}\psi \equiv \mathcal{A}\chi \text{ in } v]]$
using *Act-Basic-5* $\equiv E(1)$ *nec-imp-act*
vdash-properties-10

by blast
lemma rule-sub-lem-1-f[PLM]:

$$[\Box(\psi \equiv \chi) \text{ in } v] \implies [\Box\psi \equiv \Box\chi \text{ in } v]$$
 using KBasic-6 $\equiv I \equiv E(1)$ vdash-properties-9
 by blast

definition Substable :: $(o \Rightarrow o) \Rightarrow \text{bool}$ **where**

$$\text{Substable} \equiv \lambda \varphi . \forall \psi \chi v . (\forall w . [\psi \equiv \chi \text{ in } w]) \longrightarrow [\varphi \psi \equiv \varphi \chi \text{ in } v]$$
definition Substable1 :: $((a::\text{quantifiable} \Rightarrow o) \Rightarrow o) \Rightarrow \text{bool}$ **where**

$$\text{Substable1} \equiv \lambda \varphi . \forall \psi \chi v . (\forall x w . [\psi x \equiv \chi x \text{ in } w]) \longrightarrow [\varphi \psi \equiv \varphi \chi \text{ in } v]$$
definition Substable2 :: $((a::\text{quantifiable} \Rightarrow b::\text{quantifiable} \Rightarrow o) \Rightarrow o) \Rightarrow \text{bool}$ **where**

$$\text{Substable2} \equiv \lambda \varphi . \forall \psi \chi v . (\forall x y w . [\psi x y \equiv \chi x y \text{ in } w]) \longrightarrow [\varphi \psi \equiv \varphi \chi \text{ in } v]$$
definition SubstableVar :: $((\text{var list} \Rightarrow o) \Rightarrow o) \Rightarrow \text{bool}$ **where**

$$\text{SubstableVar} \equiv \lambda \varphi . \forall \psi \chi v . (\forall x w . [\psi x \equiv \chi x \text{ in } w]) \longrightarrow [\varphi \psi \equiv \varphi \chi \text{ in } v]$$

lemma rule-sub-nec[PLM]:
 assumes Substable φ
 shows $(\bigwedge v. [\psi \equiv \chi] \text{ in } v) \implies \Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$
proof –
 assume $(\bigwedge v. [\psi \equiv \chi] \text{ in } v)$
 hence $[\varphi \psi \text{ in } v] = [\varphi \chi \text{ in } v]$
 using assms RN unfolding Substable-def
 using $\equiv I$ CP $\equiv E(1) \equiv E(2)$ by meson
 thus $\Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$ by auto
 qed

lemma rule-sub-nec1[PLM]:
 assumes Substable1 φ
 shows $(\bigwedge v x. [\psi x \equiv \chi x] \text{ in } v) \implies \Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$
proof –
 assume $(\bigwedge v x. [\psi x \equiv \chi x] \text{ in } v)$
 hence $[\varphi \psi \text{ in } v] = [\varphi \chi \text{ in } v]$
 using assms RN unfolding Substable1-def
 using $\equiv I$ CP $\equiv E(1) \equiv E(2)$ by metis
 thus $\Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$ by auto
 qed

lemma rule-sub-nec2[PLM]:
 assumes Substable2 φ
 shows $(\bigwedge v x y. [\psi x y \equiv \chi x y \text{ in } v]) \implies \Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$
proof –
 assume $(\bigwedge v x y. [\psi x y \equiv \chi x y \text{ in } v])$
 hence $[\varphi \psi \text{ in } v] = [\varphi \chi \text{ in } v]$
 using assms RN unfolding Substable2-def
 using $\equiv I$ CP $\equiv E(1) \equiv E(2)$ by metis
 thus $\Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$ by auto
 qed

lemma rule-sub-necq[PLM]:
 assumes SubstableVar φ
 shows $(\bigwedge v x. [\psi x \equiv \chi x \text{ in } v]) \implies \Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$
proof –
 assume $(\bigwedge v x. [\psi x \equiv \chi x \text{ in } v])$
 hence $[\varphi \psi \text{ in } v] = [\varphi \chi \text{ in } v]$
 using assms RN unfolding SubstableVar-def
 using $\equiv I$ CP $\equiv E(1) \equiv E(2)$ by metis
 thus $\Theta [\varphi \psi \text{ in } v] \implies \Theta [\varphi \chi \text{ in } v]$ by auto
 qed

definition SubstableAuxVar :: $(a \Rightarrow (\text{var list} \Rightarrow o) \Rightarrow (\text{var list} \Rightarrow o)) \Rightarrow \text{bool}$ **where**

$$\begin{aligned} \text{SubstableAuxVar} &\equiv \lambda \varphi . \forall \psi \chi v x \text{ bndvars} . (\forall x v . [\psi x \equiv \chi x \text{ in } v]) \\ &\longrightarrow ([\varphi \text{ bndvars } \psi x \equiv \varphi \text{ bndvars } \chi x \text{ in } v]) \end{aligned}$$

named-theorems *Substable-intros*

lemma *SubstableVar-intro*[*Substable-intros*]:

SubstableAuxVar $\psi \implies \text{SubstableVar } (\lambda \varphi . \psi (\Theta x) \varphi x)$

unfolding *SubstableVar-def* *SubstableAuxVar-def* **by** *blast*

lemma *SubstableAux-bndvars-intro*[*Substable-intros*]:

SubstableAuxVar $(\lambda \text{ bndvars } \varphi x . \varphi (\Theta \text{ bndvars } x))$

unfolding *SubstableAuxVar-def* **using** *qml-2[axiom-instance, deduction]* **by** *blast*

lemma *SubstableAux-const-intro*[*Substable-intros*]:

SubstableAuxVar $(\lambda \text{ bndvars } \varphi x . \Theta \text{ bndvars } x)$

unfolding *SubstableAuxVar-def* **using** *oth-class-taut-4-a* **by** *blast*

lemma *SubstableAux-not-intro*[*Substable-intros*]:

SubstableAuxVar $\psi \implies \text{SubstableAuxVar } (\lambda \text{ bndvars } \varphi x .$

$\neg(\psi (\Theta 1 \text{ bndvars } x) \varphi (\Theta 2 \text{ bndvars } x)))$

unfolding *SubstableAuxVar-def*

using *rule-sub-lem-1-a* *RN-2* $\equiv E(1)$ *oth-class-taut-5-d* **by** *blast*

lemma *SubstableAux-impl-intro*[*Substable-intros*]:

SubstableAuxVar $\psi \implies \text{SubstableAuxVar } \chi \implies \text{SubstableAuxVar } (\lambda \text{ bndvars } \varphi x .$

$(\psi (\Theta 1 \text{ bndvars } x) \varphi (\Theta 2 \text{ bndvars } x)) \rightarrow (\chi (\Theta 3 \text{ bndvars } x) \varphi (\Theta 4 \text{ bndvars } x)))$

unfolding *SubstableAuxVar-def* **by** (*metis* $\equiv I$ *CP intro-elim-6-a intro-elim-6-b*)

lemma *SubstableAux-box-intro*[*Substable-intros*]:

SubstableAuxVar $\psi \implies \text{SubstableAuxVar } (\lambda \text{ bndvars } \varphi x .$

$\Box(\psi (\Theta 1 \text{ bndvars } x) \varphi (\Theta 2 \text{ bndvars } x)))$

unfolding *SubstableAuxVar-def* **using** *rule-sub-lem-1-f* *RN* **by** *meson*

lemma *SubstableAux-actual-intro*[*Substable-intros*]:

SubstableAuxVar $\psi \implies \text{SubstableAuxVar } (\lambda \text{ bndvars } \varphi x .$

$\mathcal{A}(\psi (\Theta 1 \text{ bndvars } x) \varphi (\Theta 2 \text{ bndvars } x)))$

unfolding *SubstableAuxVar-def* **using** *rule-sub-lem-1-e* *RN* **by** *meson*

lemma *SubstableAux-all-intro*[*Substable-intros*]:

SubstableAuxVar $\psi \implies \text{SubstableAuxVar } (\lambda \text{ bndvars } \varphi x .$

$\forall y . (\psi (\Theta 1 \text{ bndvars } x y) \varphi (\Theta 2 \text{ bndvars } x y)))$

unfolding *SubstableAuxVar-def*

proof (*rule allI*)+

fix $\Psi \chi :: \text{var list} \Rightarrow \text{o}$ **and** $v x \text{ bndvars}$

assume *a1*: $\forall \Psi \chi v x \text{ bndvars} . (\forall x w . [\Psi x \equiv \chi x \text{ in } w])$

$\longrightarrow [\psi \text{ bndvars } \Psi x \equiv \psi \text{ bndvars } \chi x \text{ in } v]$

{
 assume *a2*: $(\forall x v . [\Psi x \equiv \chi x \text{ in } v])$

{

fix y

have $[\psi (\Theta 1 \text{ bndvars } x y) \Psi (\Theta 2 \text{ bndvars } x y)]$

$\equiv \psi (\Theta 1 \text{ bndvars } x y) \chi (\Theta 2 \text{ bndvars } x y) \text{ in } v]$

using *a1 a2* **by** *auto*

}

hence $[(\forall y . \psi (\Theta 1 \text{ bndvars } x y) \Psi (\Theta 2 \text{ bndvars } x y))$

$\equiv (\forall y . \psi (\Theta 1 \text{ bndvars } x y) \chi (\Theta 2 \text{ bndvars } x y)) \text{ in } v]$

using *cqt-basic-3[deduction]* $\forall I$ **by** *fast*

}

thus $(\forall x v . [\Psi x \equiv \chi x \text{ in } v]) \longrightarrow$

$[(\forall y . \psi (\Theta 1 \text{ bndvars } x y) \Psi (\Theta 2 \text{ bndvars } x y))$

$\equiv (\forall y . \psi (\Theta 1 \text{ bndvars } x y) \chi (\Theta 2 \text{ bndvars } x y)) \text{ in } v]$

by *auto*

qed

lemma *Substable-intro*[*Substable-intros*]:

SubstableVar $(\lambda \varphi . \psi \varphi) \implies \text{Substable } (\lambda \varphi . \psi (\lambda v . \varphi))$

unfolding *SubstableVar-def* *Substable-def* **by** *fast*

lemma *Substable1-intro*[*Substable-intros*]:

SubstableVar $(\lambda \varphi . \psi (\lambda y . \varphi ((\text{qvar } y) \# \text{Nil}))) \implies \text{Substable1 } \psi$

unfolding *SubstableVar-def Substable1-def*
proof (*rule allI*)+
fix $\Psi :: 'a::\text{quantifiable} \Rightarrow o$ **and** χv
assume $1: \forall \Psi \chi v.$
 $(\forall x w. [\Psi x \equiv \chi x \text{ in } w]) \longrightarrow [\psi (\lambda y. \Psi ((qvar y) \# Nil))$
 $\equiv \psi (\lambda y. \chi ((qvar y) \# Nil)) \text{ in } v]$
{
assume $(\forall x w. [\Psi x \equiv \chi x \text{ in } w])$
hence $[\psi (\lambda y. \Psi (varq (hd ((qvar y) \# Nil))))$
 $\equiv \psi (\lambda y. \chi (varq (hd ((qvar y) \# Nil)))) \text{ in } v]$
using 1 **by** *fast*
hence $[\psi (\lambda y. \Psi y) \equiv \psi (\lambda y. \chi y) \text{ in } v]$
using *varq-qvar-id* [**where** $'a = 'a$] **by** *fastforce*
}
thus $(\forall x w. [\Psi x \equiv \chi x \text{ in } w]) \longrightarrow [\psi \Psi \equiv \psi \chi \text{ in } v]$
by *blast*
qed

lemma *Substable2-intro*[*Substable-intros*]:
 $SubstableVar (\lambda \varphi. \psi (\lambda x y. \varphi ((qvar x) \# (qvar y) \# Nil))) \Longrightarrow Substable2 \psi$
unfolding *SubstableVar-def Substable2-def*
proof (*rule allI*)+
fix $\Psi :: 'a::\text{quantifiable} \Rightarrow 'b::\text{quantifiable} \Rightarrow o$ **and** χv
let $?L = \lambda x y. (qvar x) \# (qvar y) \# Nil$
assume $1: \forall \Psi \chi v. (\forall x w. [\Psi x \equiv \chi x \text{ in } w])$
 $\longrightarrow [\psi (\lambda x y. \Psi (?L x y)) \equiv \psi (\lambda x y. \chi (?L x y)) \text{ in } v]$
{
assume $\forall x y w. [\Psi x y \equiv \chi x y \text{ in } w]$
hence $[\psi (\lambda x y. \Psi (varq (hd (?L x y))) (varq (hd (tl (?L x y))))$
 $\equiv \psi (\lambda x y. \chi (varq (hd (?L x y))) (varq (hd (tl (?L x y)))) \text{ in } v]$
using 1 **by** *fast*
hence $[\psi (\lambda x y. \Psi x y) \equiv \psi (\lambda x y. \chi x y) \text{ in } v]$
using *varq-qvar-id* [**where** $'a = 'a$] *varq-qvar-id* [**where** $'a = 'b$] **by** *fastforce*
}
thus $(\forall x y w. [\Psi x y \equiv \chi x y \text{ in } w]) \longrightarrow [\psi \Psi \equiv \psi \chi \text{ in } v]$
by *blast*
qed

lemma *SubstableAux-conj-intro*[*Substable-intros*]:
 $SubstableAuxVar \psi \Longrightarrow SubstableAuxVar \chi \Longrightarrow SubstableAuxVar (\lambda bndvars \varphi x.$
 $(\psi (\Theta 1 bndvars x) \varphi (\Theta 2 bndvars x)) \ \& \ (\chi (\Theta 3 bndvars x) \varphi (\Theta 5 bndvars x)))$
unfolding *conn-defs* **by** $((\text{rule } Substable-intros)+; ((\text{assumption}+) ?)) +$
lemma *SubstableAux-disj-intro*[*Substable-intros*]:
 $SubstableAuxVar \psi \Longrightarrow SubstableAuxVar \chi \Longrightarrow SubstableAuxVar (\lambda bndvars \varphi x.$
 $(\psi (\Theta 1 bndvars x) \varphi (\Theta 2 bndvars x)) \vee (\chi (\Theta 3 bndvars x) \varphi (\Theta 4 bndvars x)))$
unfolding *conn-defs* **by** $((\text{rule } Substable-intros)+; ((\text{assumption}+) ?)) +$
lemma *SubstableAux-equiv-intro*[*Substable-intros*]:
 $SubstableAuxVar \psi \Longrightarrow SubstableAuxVar \chi \Longrightarrow SubstableAuxVar (\lambda bndvars \varphi x.$
 $(\psi (\Theta 1 bndvars x) \varphi (\Theta 2 bndvars x)) \equiv (\chi (\Theta 3 bndvars x) \varphi (\Theta 4 bndvars x)))$
unfolding *conn-defs* **by** $((\text{rule } Substable-intros)+; ((\text{assumption}+) ?)) +$
lemma *SubstableAux-diamond-intro*[*Substable-intros*]:
 $SubstableAuxVar \psi \Longrightarrow SubstableAuxVar (\lambda bndvars \varphi x.$
 $\Diamond (\psi (\Theta 1 bndvars x) \varphi (\Theta 2 bndvars x)))$
unfolding *conn-defs* **by** $((\text{rule } Substable-intros)+; ((\text{assumption}+) ?)) +$
lemma *SubstableAux-exists-intro*[*Substable-intros*]:
 $SubstableAuxVar \psi \Longrightarrow SubstableAuxVar (\lambda bndvars \varphi x.$
 $\exists y. (\psi (\Theta 1 bndvars x y) \varphi (\Theta 2 bndvars x y)))$
unfolding *conn-defs* **by** $((\text{rule } Substable-intros)+; ((\text{assumption}+) ?)) +$

method *PLM-subst-method* **for** $\psi::o$ **and** $\chi::o =$
 $(\text{match } \text{conclusion in } \Theta [\varphi \chi \text{ in } v] \text{ for } \Theta \text{ and } \varphi \text{ and } v \Rightarrow$
 $\langle (\text{rule } \text{rule-sub-nec} [\text{where } \Theta = \Theta \text{ and } \chi = \chi \text{ and } \psi = \psi \text{ and } \varphi = \varphi \text{ and } v = v],$


```

    ((rule Substable-intros, ((assumption)+)?+; fail)))
method PLM-subst-goal-method for  $\varphi::o \Rightarrow o$  and  $\psi::o =$ 
  (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\chi$  and  $v \Rightarrow$ 
    ((rule rule-sub-nec[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
      ((rule Substable-intros, ((assumption)+)?+; fail))))
method PLM-subst1-method for  $\psi::('a::\text{quantifiable}) \Rightarrow o$  and  $\chi::('a) \Rightarrow o =$ 
  (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\varphi$  and  $v \Rightarrow$ 
    ((rule rule-sub-nec1[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
      ((rule Substable-intros, ((assumption)+)?+; fail))))
method PLM-subst1-goal-method for  $\varphi::('a::\text{quantifiable} \Rightarrow o) \Rightarrow o$  and  $\psi::'a \Rightarrow o =$ 
  (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\chi$  and  $v \Rightarrow$ 
    ((rule rule-sub-nec1[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
      ((rule Substable-intros, ((assumption)+)?+; fail))))
method PLM-subst2-method for  $\psi::'a::\text{quantifiable} \Rightarrow 'a \Rightarrow o$  and  $\chi::'a \Rightarrow 'a \Rightarrow o =$ 
  (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\varphi$  and  $v \Rightarrow$ 
    ((rule rule-sub-nec2[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
      ((rule Substable-intros, ((assumption)+)?+; fail))))
method PLM-subst2-goal-method for  $\varphi::('a::\text{quantifiable} \Rightarrow 'a \Rightarrow o) \Rightarrow o$ 
  and  $\psi::'a \Rightarrow 'a \Rightarrow o =$ 
  (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\chi$  and  $v \Rightarrow$ 
    ((rule rule-sub-nec2[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
      ((rule Substable-intros, ((assumption)+)?+; fail))))

method PLM-autosubst =
  (match premises in  $\bigwedge v . [\psi \equiv \chi \text{ in } v]$  for  $\psi$  and  $\chi \Rightarrow$ 
    (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$   $\varphi$  and  $v \Rightarrow$ 
      ((rule rule-sub-nec[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
        ((rule Substable-intros, ((assumption)+)?+; fail)))) )
method PLM-autosubst-with uses WITH =
  (match WITH in  $Y: \bigwedge v . [\psi \equiv \chi \text{ in } v]$  for  $\psi$  and  $\chi \Rightarrow$ 
    (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\varphi$  and  $v \Rightarrow$ 
      ((rule rule-sub-nec[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
        ((rule Substable-intros)+; fail)), ((fact WITH)?+; fail)) )
method PLM-autosubst1 =
  (match premises in  $\bigwedge v x :: 'a::\text{quantifiable} . [\psi x \equiv \chi x \text{ in } v]$  for  $\psi$  and  $\chi \Rightarrow$ 
    (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\varphi$  and  $v \Rightarrow$ 
      ((rule rule-sub-nec1[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
        ((rule Substable-intros, ((assumption)+)?+; fail)))) )
method PLM-autosubst2 =
  (match premises in  $\bigwedge v (x :: 'a::\text{quantifiable}) (y::'a) . [\psi x y \equiv \chi x y \text{ in } v]$ 
    for  $\psi$  and  $\chi \Rightarrow$ 
    (match conclusion in  $\Theta [\varphi \chi \text{ in } v]$  for  $\Theta$  and  $\varphi$  and  $v \Rightarrow$ 
      ((rule rule-sub-nec2[where  $\Theta=\Theta$  and  $\chi=\chi$  and  $\psi=\psi$  and  $\varphi=\varphi$  and  $v=v$ ],
        ((rule Substable-intros, ((assumption)+)?+; fail)))) )

```

lemma rule-sub-remark-1:

```

assumes ( $\bigwedge v. [\llbracket A!, x \rrbracket \equiv (\neg(\Diamond \llbracket E!, x \rrbracket)) \text{ in } v]$ )
and [ $\neg \llbracket A!, x \rrbracket \text{ in } v$ ]
shows [ $\neg \neg \Diamond \llbracket E!, x \rrbracket \text{ in } v$ ]
apply (insert assms) apply PLM-autosubst by auto

```

lemma rule-sub-remark-2:

```

assumes ( $\bigwedge v. [\llbracket R, x, y \rrbracket \equiv (\llbracket R, x, y \rrbracket \ \& \ (\llbracket Q, a \rrbracket \vee (\neg \llbracket Q, a \rrbracket))) \text{ in } v]$ )
and [ $p \rightarrow \llbracket R, x, y \rrbracket \text{ in } v$ ]
shows [ $p \rightarrow (\llbracket R, x, y \rrbracket \ \& \ (\llbracket Q, a \rrbracket \vee (\neg \llbracket Q, a \rrbracket))) \text{ in } v$ ]
apply (insert assms) apply PLM-autosubst by auto

```

lemma rule-sub-remark-3:

```

assumes ( $\bigwedge v x. [\llbracket A!, x^P \rrbracket \equiv (\neg(\Diamond \llbracket E!, x^P \rrbracket)) \text{ in } v]$ )
and [ $\exists x . \llbracket A!, x^P \rrbracket \text{ in } v$ ]
shows [ $\exists x . (\neg(\Diamond \llbracket E!, x^P \rrbracket)) \text{ in } v$ ]
apply (insert assms) apply PLM-autosubst1 by auto

```

lemma *rule-sub-remark-4*:
 assumes $\bigwedge v x. [\neg(\neg(P, x^P))] \equiv (P, x^P) \text{ in } v]$
 and $[\mathcal{A}(\neg(\neg(P, x^P))) \text{ in } v]$
 shows $[\mathcal{A}(P, x^P) \text{ in } v]$
 apply (*insert assms*) **apply** *PLM-autosubst1* **by** *auto*

lemma *rule-sub-remark-5*:
 assumes $\bigwedge v. [\varphi \rightarrow \psi] \equiv ((\neg\psi) \rightarrow (\neg\varphi)) \text{ in } v]$
 and $[\Box(\varphi \rightarrow \psi) \text{ in } v]$
 shows $[\Box((\neg\psi) \rightarrow (\neg\varphi)) \text{ in } v]$
 apply (*insert assms*) **apply** *PLM-autosubst* **by** *auto*

lemma *rule-sub-remark-6*:
 assumes $\bigwedge v. [\psi \equiv \chi \text{ in } v]$
 and $[\Box(\varphi \rightarrow \psi) \text{ in } v]$
 shows $[\Box(\varphi \rightarrow \chi) \text{ in } v]$
 apply (*insert assms*) **apply** *PLM-autosubst* **by** *auto*

lemma *rule-sub-remark-7*:
 assumes $\bigwedge v. [\varphi \equiv (\neg(\neg\varphi)) \text{ in } v]$
 and $[\Box(\varphi \rightarrow \varphi) \text{ in } v]$
 shows $[\Box((\neg(\neg\varphi)) \rightarrow \varphi) \text{ in } v]$
 apply (*insert assms*) **apply** *PLM-autosubst* **by** *auto*

lemma *rule-sub-remark-8*:
 assumes $\bigwedge v. [\mathcal{A}\varphi \equiv \varphi \text{ in } v]$
 and $[\Box(\mathcal{A}\varphi) \text{ in } v]$
 shows $[\Box(\varphi) \text{ in } v]$
 apply (*insert assms*) **apply** *PLM-autosubst* **by** *auto*

lemma *rule-sub-remark-9*:
 assumes $\bigwedge v. [(P, a) \equiv ((P, a) \ \& \ ((Q, b) \vee (\neg(Q, b)))) \text{ in } v]$
 and $[(P, a) = (P, a) \text{ in } v]$
 shows $[(P, a) = ((P, a) \ \& \ ((Q, b) \vee (\neg(Q, b)))) \text{ in } v]$
 unfolding *identity-defs* **apply** (*insert assms*)
apply *PLM-autosubst* **oops** — no match as desired

— *dr-alphabetic-rules* implicitly holds
 — *dr-alphabetic-thm* implicitly holds

lemma *KBasic2-1*[*PLM*]:
 $[\Box\varphi \equiv \Box(\neg(\neg\varphi)) \text{ in } v]$
apply (*PLM-subst-method* $\varphi \ (\neg(\neg\varphi))$)
by *PLM-solver+*

lemma *KBasic2-2*[*PLM*]:
 $[(\neg(\Box\varphi)) \equiv \Diamond(\neg\varphi) \text{ in } v]$
 unfolding *diamond-def*
apply (*PLM-subst-method* $\varphi \ \neg(\neg\varphi)$)
by *PLM-solver+*

lemma *KBasic2-3*[*PLM*]:
 $[\Box\varphi \equiv (\neg(\Diamond(\neg\varphi))) \text{ in } v]$
 unfolding *diamond-def*
apply (*PLM-subst-method* $\varphi \ \neg(\neg\varphi)$)
apply *PLM-solver*
by (*simp add: oth-class-taut-4-b*)

lemmas *Df* $\Box = KBasic2-3$

lemma *KBasic2-4*[*PLM*]:
 $[\Box(\neg(\varphi)) \equiv (\neg(\Diamond\varphi)) \text{ in } v]$
 unfolding *diamond-def*
by (*simp add: oth-class-taut-4-b*)

lemma *KBasic2-5[PLM]*:

$[\Box(\varphi \rightarrow \psi) \rightarrow (\Diamond\varphi \rightarrow \Diamond\psi) \text{ in } v]$

by (*simp only: CP RM-2-b*)

lemmas $K\Diamond = KBasic2-5$

lemma *KBasic2-6[PLM]*:

$[\Diamond(\varphi \vee \psi) \equiv (\Diamond\varphi \vee \Diamond\psi) \text{ in } v]$

proof –

have $[\Box((\neg\varphi) \ \& \ (\neg\psi)) \equiv (\Box(\neg\varphi) \ \& \ \Box(\neg\psi)) \text{ in } v]$

using *KBasic-3* **by** *blast*

hence $[(\neg(\Diamond(\neg(\neg\varphi) \ \& \ (\neg\psi)))) \equiv (\Box(\neg\varphi) \ \& \ \Box(\neg\psi)) \text{ in } v]$

using *DfBox* **by** (*rule* $\equiv E(6)$)

hence $[(\neg(\Diamond(\neg(\neg\varphi) \ \& \ (\neg\psi)))) \equiv ((\neg(\Diamond\varphi)) \ \& \ (\neg(\Diamond\psi))) \text{ in } v]$

apply *cut-tac* **apply** (*PLM-subst-method* $\Box(\neg\varphi) \ \neg(\Diamond\varphi)$)

apply (*rule* *KBasic2-4*)

apply (*PLM-subst-method* $\Box(\neg\psi) \ \neg(\Diamond\psi)$)

apply (*rule* *KBasic2-4*)

unfolding *diamond-def* **by** *assumption*

hence $[(\neg(\Diamond(\varphi \vee \psi))) \equiv ((\neg(\Diamond\varphi)) \ \& \ (\neg(\Diamond\psi))) \text{ in } v]$

apply *cut-tac* **apply** (*PLM-subst-method* $\neg((\neg\varphi) \ \& \ (\neg\psi)) \ \varphi \vee \psi$)

using *oth-class-taut-6-b[equiv-sym]* **by** *auto*

hence $[(\neg(\neg(\Diamond(\varphi \vee \psi)))) \equiv (\neg((\neg(\Diamond\varphi)) \ \& \ (\neg(\Diamond\psi)))) \text{ in } v]$

by (*rule* *oth-class-taut-5-d[equiv-lr]*)

hence $[\Diamond(\varphi \vee \psi) \equiv (\neg((\neg(\Diamond\varphi)) \ \& \ (\neg(\Diamond\psi)))) \text{ in } v]$

apply *cut-tac* **apply** (*PLM-subst-method* $\neg(\neg(\Diamond(\varphi \vee \psi))) \ \Diamond(\varphi \vee \psi)$)

using *oth-class-taut-4-b[equiv-sym]* **by** *assumption+*

thus *?thesis*

apply *cut-tac* **apply** (*PLM-subst-method* $\neg((\neg(\Diamond\varphi)) \ \& \ (\neg(\Diamond\psi))) \ (\Diamond\varphi) \vee (\Diamond\psi)$)

using *oth-class-taut-6-b[equiv-sym]* **by** *assumption+*

qed

lemma *KBasic2-7[PLM]*:

$[(\Box\varphi \vee \Box\psi) \rightarrow \Box(\varphi \vee \psi) \text{ in } v]$

proof –

have $\bigwedge v. [\varphi \rightarrow (\varphi \vee \psi) \text{ in } v]$

by (*metis contraposition-1 contraposition-2 useful-tautologies-3 disj-def*)

hence $[\Box\varphi \rightarrow \Box(\varphi \vee \psi) \text{ in } v]$ **using** *RM-1* **by** *auto*

moreover {

have $\bigwedge v. [\psi \rightarrow (\varphi \vee \psi) \text{ in } v]$

by (*simp only: pl-1[axiom-instance] disj-def*)

hence $[\Box\psi \rightarrow \Box(\varphi \vee \psi) \text{ in } v]$

using *RM-1* **by** *auto*

}

ultimately show *?thesis*

using *oth-class-taut-10-d vdash-properties-10* **by** *blast*

qed

lemma *KBasic2-8[PLM]*:

$[\Diamond(\varphi \ \& \ \psi) \rightarrow (\Diamond\varphi \ \& \ \Diamond\psi) \text{ in } v]$

by (*metis CP RM-2 &I oth-class-taut-9-a*

oth-class-taut-9-b vdash-properties-10)

lemma *KBasic2-9[PLM]*:

$[\Diamond(\varphi \rightarrow \psi) \equiv (\Box\varphi \rightarrow \Diamond\psi) \text{ in } v]$

apply (*PLM-subst-method* $(\neg(\Box\varphi)) \vee (\Diamond\psi) \ \Box\varphi \rightarrow \Diamond\psi$)

using *oth-class-taut-5-k[equiv-sym]* **apply** *assumption*

apply (*PLM-subst-method* $(\neg\varphi) \vee \psi \ \varphi \rightarrow \psi$)

using *oth-class-taut-5-k[equiv-sym]* **apply** *assumption*

apply (*PLM-subst-method* $\Diamond(\neg\varphi) \ \neg(\Box\varphi)$)

using *KBasic2-2[equiv-sym]* **apply** *assumption*

using *KBasic2-6* .

lemma *KBasic2-10*[*PLM*]:
 $[\Diamond(\Box\varphi) \equiv (\neg(\Box\Diamond(\neg\varphi))) \text{ in } v]$
unfolding *diamond-def* **apply** (*PLM-subst-method* $\varphi \neg\neg\varphi$)
using *oth-class-taut-4-b* *oth-class-taut-4-a* **by** *auto*

lemma *KBasic2-11*[*PLM*]:
 $[\Diamond\Diamond\varphi \equiv (\neg(\Box\Box(\neg\varphi))) \text{ in } v]$
unfolding *diamond-def*
apply (*PLM-subst-method* $\Box(\neg\varphi) \neg(\neg(\Box(\neg\varphi)))$)
using *oth-class-taut-4-b* *oth-class-taut-4-a* **by** *auto*

lemma *KBasic2-12*[*PLM*]: $[\Box(\varphi \vee \psi) \rightarrow (\Box\varphi \vee \Diamond\psi) \text{ in } v]$
proof –
have $[\Box(\psi \vee \varphi) \rightarrow (\Box(\neg\psi) \rightarrow \Box\varphi) \text{ in } v]$
using *CP* *RM-1-b* $\vee E(2)$ **by** *blast*
hence $[\Box(\psi \vee \varphi) \rightarrow (\Diamond\psi \vee \Box\varphi) \text{ in } v]$
unfolding *diamond-def* *disj-def*
by (*meson* *CP* $\neg\neg E$ *vdash-properties-6*)
thus *?thesis* **apply** *cut-tac*
apply (*PLM-subst-method* $(\Diamond\psi \vee \Box\varphi) (\Box\varphi \vee \Diamond\psi)$)
apply (*simp add: PLM.oth-class-taut-3-e*)
apply (*PLM-subst-method* $(\psi \vee \varphi) (\varphi \vee \psi)$)
apply (*simp add: PLM.oth-class-taut-3-e*)
by *assumption*
qed

lemma *TBasic*[*PLM*]:
 $[\varphi \rightarrow \Diamond\varphi \text{ in } v]$
unfolding *diamond-def*
apply (*subst contraposition-1*)
apply (*PLM-subst-method* $\Box\neg\varphi \neg\neg\Box\neg\varphi$)
apply (*simp only: PLM.oth-class-taut-4-b*)
using *qml-2*[**where** $\varphi=\neg\varphi$, *axiom-instance*]
by *assumption*

lemmas $T\Diamond = TBasic$

lemma *S5Basic-1*[*PLM*]:
 $[\Diamond\Box\varphi \rightarrow \Box\varphi \text{ in } v]$
proof (*rule CP*)
assume $[\Diamond\Box\varphi \text{ in } v]$
hence $[\neg\Box\Diamond\neg\varphi \text{ in } v]$
using *KBasic2-10*[*equiv-lr*] **by** *simp*
moreover **have** $[\Diamond(\neg\varphi) \rightarrow \Box\Diamond(\neg\varphi) \text{ in } v]$
by (*simp add: qml-3*[*axiom-instance*])
ultimately **have** $[\neg\Diamond\neg\varphi \text{ in } v]$
by (*simp add: PLM.modus-tollens-1*)
thus $[\Box\varphi \text{ in } v]$
unfolding *diamond-def* **apply** *cut-tac*
apply (*PLM-subst-method* $\neg\neg\varphi \varphi$)
using *oth-class-taut-4-b*[*equiv-sym*] **apply** *assumption*
unfolding *diamond-def* **using** *oth-class-taut-4-b*[*equiv-rl*]
by *simp*
qed

lemmas $5\Diamond = S5Basic-1$

lemma *S5Basic-2*[*PLM*]:
 $[\Box\varphi \equiv \Diamond\Box\varphi \text{ in } v]$
using $5\Diamond$ $T\Diamond \equiv I$ **by** *blast*

lemma *S5Basic-3*[*PLM*]:
 $[\Diamond\varphi \equiv \Box\Diamond\varphi \text{ in } v]$
using *qml-3*[*axiom-instance*] *qml-2*[*axiom-instance*] $\equiv I$ **by** *blast*

lemma *S5Basic-4*[PLM]:
 $[\varphi \rightarrow \Box\Diamond\varphi \text{ in } v]$
using *T* \Diamond [deduction, THEN *S5Basic-3*[equiv-lr]]
by (rule CP)

lemma *S5Basic-5*[PLM]:
 $[\Diamond\Box\varphi \rightarrow \varphi \text{ in } v]$
using *S5Basic-2*[equiv-rl, THEN *qml-2*[axiom-instance, deduction]]
by (rule CP)
lemmas $B\Diamond = S5Basic-5$

lemma *S5Basic-6*[PLM]:
 $[\Box\varphi \rightarrow \Box\Box\varphi \text{ in } v]$
using *S5Basic-4*[deduction] *RM-1*[OF *S5Basic-1*, deduction] CP **by** auto
lemmas $4\Box = S5Basic-6$

lemma *S5Basic-7*[PLM]:
 $[\Box\varphi \equiv \Box\Box\varphi \text{ in } v]$
using $4\Box$ *qml-2*[axiom-instance] **by** (rule $\equiv I$)

lemma *S5Basic-8*[PLM]:
 $[\Diamond\Diamond\varphi \rightarrow \Diamond\varphi \text{ in } v]$
using *S5Basic-6*[**where** $\varphi = \neg\varphi$, THEN *contraposition-1*[THEN *iffD1*], deduction]
KBasic2-11[equiv-lr] CP **unfolding** *diamond-def* **by** auto
lemmas $4\Diamond = S5Basic-8$

lemma *S5Basic-9*[PLM]:
 $[\Diamond\Diamond\varphi \equiv \Diamond\varphi \text{ in } v]$
using $4\Diamond$ *T* \Diamond **by** (rule $\equiv I$)

lemma *S5Basic-10*[PLM]:
 $[\Box(\varphi \vee \Box\psi) \equiv (\Box\varphi \vee \Box\psi) \text{ in } v]$
apply (rule $\equiv I$)
apply (*PLM-subst-goal-method* $\lambda \chi . \Box(\varphi \vee \Box\psi) \rightarrow (\Box\varphi \vee \chi) \Diamond\Box\psi$)
using *S5Basic-2*[equiv-sym] **apply** assumption
using *KBasic2-12* **apply** assumption
apply (*PLM-subst-goal-method* $\lambda \chi . (\Box\varphi \vee \chi) \rightarrow \Box(\varphi \vee \Box\psi) \Box\Box\psi$)
using *S5Basic-7*[equiv-sym] **apply** assumption
using *KBasic2-7* **by** auto

lemma *S5Basic-11*[PLM]:
 $[\Box(\varphi \vee \Diamond\psi) \equiv (\Box\varphi \vee \Diamond\psi) \text{ in } v]$
apply (rule $\equiv I$)
apply (*PLM-subst-goal-method* $\lambda \chi . \Box(\varphi \vee \Diamond\psi) \rightarrow (\Box\varphi \vee \chi) \Diamond\Diamond\psi$)
using *S5Basic-9* **apply** assumption
using *KBasic2-12* **apply** assumption
apply (*PLM-subst-goal-method* $\lambda \chi . (\Box\varphi \vee \chi) \rightarrow \Box(\varphi \vee \Diamond\psi) \Box\Diamond\psi$)
using *S5Basic-3*[equiv-sym] **apply** assumption
using *KBasic2-7* **by** assumption

lemma *S5Basic-12*[PLM]:
 $[\Diamond(\varphi \ \& \ \Diamond\psi) \equiv (\Diamond\varphi \ \& \ \Diamond\psi) \text{ in } v]$
proof –
have $[\Box((\neg\varphi) \vee \Box(\neg\psi)) \equiv (\Box(\neg\varphi) \vee \Box(\neg\psi)) \text{ in } v]$
using *S5Basic-10* **by** auto
hence 1: $[(\neg\Box((\neg\varphi) \vee \Box(\neg\psi))) \equiv \neg(\Box(\neg\varphi) \vee \Box(\neg\psi)) \text{ in } v]$
using *oth-class-taut-5-d*[equiv-lr] **by** auto
have 2: $[(\Diamond(\neg((\neg\varphi) \vee (\neg\Diamond\psi)))) \equiv (\neg((\neg\Diamond\varphi) \vee (\neg\Diamond\psi))) \text{ in } v]$
apply (*PLM-subst-method* $\Box\neg\psi \neg\Diamond\psi$)
using *KBasic2-4* **apply** assumption
apply (*PLM-subst-method* $\Box\neg\varphi \neg\Diamond\varphi$)
using *KBasic2-4* **apply** assumption
apply (*PLM-subst-method* $(\neg\Box((\neg\varphi) \vee \Box(\neg\psi))) (\Diamond(\neg((\neg\varphi) \vee (\Box(\neg\psi)))))$)

```

    unfolding diamond-def
    apply (simp add: RN oth-class-taut-4-b rule-sub-lem-1-a rule-sub-lem-1-f)
    using 1 by assumption
  show ?thesis
    apply (PLM-subst-method  $\neg((\neg\varphi) \vee (\neg\Diamond\psi)) \varphi \ \& \ \Diamond\psi$ )
    using oth-class-taut-6-a[equiv-sym] apply assumption
    apply (PLM-subst-method  $\neg((\neg(\Diamond\varphi)) \vee (\neg\Diamond\psi)) \Diamond\varphi \ \& \ \Diamond\psi$ )
    using oth-class-taut-6-a[equiv-sym] apply assumption
    using 2 by assumption
qed

```

```

lemma S5Basic-13[PLM]:
   $[\Diamond(\varphi \ \& \ (\Box\psi)) \equiv (\Diamond\varphi \ \& \ (\Box\psi)) \text{ in } v]$ 
  apply (PLM-subst-method  $\Diamond\Box\psi \ \Box\psi$ )
  using S5Basic-2[equiv-sym] apply assumption
  using S5Basic-12 by simp

```

```

lemma S5Basic-14[PLM]:
   $[\Box(\varphi \rightarrow (\Box\psi)) \equiv \Box(\Diamond\varphi \rightarrow \psi) \text{ in } v]$ 
  proof (rule  $\equiv I$ ; rule CP)
    assume  $[\Box(\varphi \rightarrow \Box\psi) \text{ in } v]$ 
    moreover {
      have  $\bigwedge v. [\Box(\varphi \rightarrow \Box\psi) \rightarrow (\Diamond\varphi \rightarrow \psi) \text{ in } v]$ 
      proof (rule CP)
        fix v
        assume  $[\Box(\varphi \rightarrow \Box\psi) \text{ in } v]$ 
        hence  $[\Diamond\varphi \rightarrow \Diamond\Box\psi \text{ in } v]$ 
        using  $K\Diamond$ [deduction] by auto
        thus  $[\Diamond\varphi \rightarrow \psi \text{ in } v]$ 
        using  $B\Diamond$  ded-thm-cor-3 by blast
      qed
      hence  $[\Box(\Box(\varphi \rightarrow \Box\psi) \rightarrow (\Diamond\varphi \rightarrow \psi)) \text{ in } v]$ 
      by (rule RN)
      hence  $[\Box(\Box(\varphi \rightarrow \Box\psi)) \rightarrow \Box((\Diamond\varphi \rightarrow \psi)) \text{ in } v]$ 
      using qml-1[axiom-instance, deduction] by auto
    }
    ultimately show  $[\Box(\Diamond\varphi \rightarrow \psi) \text{ in } v]$ 
    using S5Basic-6 CP vdash-properties-10 by meson
  next
    assume  $[\Box(\Diamond\varphi \rightarrow \psi) \text{ in } v]$ 
    moreover {
      fix v
      {
        assume  $[\Box(\Diamond\varphi \rightarrow \psi) \text{ in } v]$ 
        hence 1:  $[\Box\Diamond\varphi \rightarrow \Box\psi \text{ in } v]$ 
        using qml-1[axiom-instance, deduction] by auto
        assume  $[\varphi \text{ in } v]$ 
        hence  $[\Box\Diamond\varphi \text{ in } v]$ 
        using S5Basic-4[deduction] by auto
        hence  $[\Box\psi \text{ in } v]$ 
        using 1[deduction] by auto
      }
      hence  $[\Box(\Diamond\varphi \rightarrow \psi) \text{ in } v] \implies [\varphi \rightarrow \Box\psi \text{ in } v]$ 
      using CP by auto
    }
    ultimately show  $[\Box(\varphi \rightarrow \Box\psi) \text{ in } v]$ 
    using S5Basic-6 RN-2 vdash-properties-10 by blast
  qed

```

```

lemma sc-eq-box-box-1[PLM]:
   $[\Box(\varphi \rightarrow \Box\varphi) \rightarrow (\Diamond\varphi \equiv \Box\varphi) \text{ in } v]$ 
  proof (rule CP)
    assume 1:  $[\Box(\varphi \rightarrow \Box\varphi) \text{ in } v]$ 

```

```

hence  $\Box(\Diamond\varphi \rightarrow \varphi)$  in  $v$ 
  using S5Basic-14[equiv-lr] by auto
hence  $\Diamond\varphi \rightarrow \varphi$  in  $v$ 
  using qml-2[axiom-instance, deduction] by auto
moreover from 1 have  $\varphi \rightarrow \Box\varphi$  in  $v$ 
  using qml-2[axiom-instance, deduction] by auto
ultimately have  $\Diamond\varphi \rightarrow \Box\varphi$  in  $v$ 
  using ded-thm-cor-3 by auto
moreover have  $\Box\varphi \rightarrow \Diamond\varphi$  in  $v$ 
  using qml-2[axiom-instance] T $\Diamond$ 
  by (rule ded-thm-cor-3)
ultimately show  $\Diamond\varphi \equiv \Box\varphi$  in  $v$ 
  by (rule  $\equiv I$ )
qed

```

lemma *sc-eq-box-box-2*[*PLM*]:
 $\Box(\varphi \rightarrow \Box\varphi) \rightarrow ((\neg\Box\varphi) \equiv (\Box(\neg\varphi)))$ in v
proof (rule *CP*)
 assume $\Box(\varphi \rightarrow \Box\varphi)$ in v
 hence $(\neg\Box(\neg\varphi)) \equiv \Box\varphi$ in v
 using *sc-eq-box-box-1*[*deduction*] **unfolding** *diamond-def* by auto
 thus $((\neg\Box\varphi) \equiv (\Box(\neg\varphi)))$ in v
 by (*meson* *CP* $\equiv I \equiv E(3)$
 $\equiv E(4) \neg I \neg E$)
 qed

lemma *sc-eq-box-box-3*[*PLM*]:
 $(\Box(\varphi \rightarrow \Box\varphi) \ \& \ \Box(\psi \rightarrow \Box\psi)) \rightarrow ((\Box\varphi \equiv \Box\psi) \rightarrow \Box(\varphi \equiv \psi))$ in v
proof (rule *CP*)
 assume 1: $(\Box(\varphi \rightarrow \Box\varphi) \ \& \ \Box(\psi \rightarrow \Box\psi))$ in v
 {
 assume $\Box\varphi \equiv \Box\psi$ in v
 hence $(\Box\varphi \ \& \ \Box\psi) \vee ((\neg\Box\varphi) \ \& \ (\neg\Box\psi))$ in v
 using *oth-class-taut-5-i*[*equiv-lr*] by auto
 moreover {
 assume $\Box\varphi \ \& \ \Box\psi$ in v
 hence $\Box(\varphi \equiv \psi)$ in v
 using *KBasic-7*[*deduction*] by auto
 }
 moreover {
 assume $(\neg\Box\varphi) \ \& \ (\neg\Box\psi)$ in v
 hence $\Box(\neg\varphi) \ \& \ \Box(\neg\psi)$ in v
 using 1 & *E* & *I* *sc-eq-box-box-2*[*deduction*, *equiv-lr*]
 by *metis*
 hence $\Box((\neg\varphi) \ \& \ (\neg\psi))$ in v
 using *KBasic-3*[*equiv-rl*] by auto
 hence $\Box(\varphi \equiv \psi)$ in v
 using *KBasic-9*[*deduction*] by auto
 }
 ultimately have $\Box(\varphi \equiv \psi)$ in v
 using *CP* $\vee E(1)$ by *blast*
 }
 thus $\Box\varphi \equiv \Box\psi \rightarrow \Box(\varphi \equiv \psi)$ in v
 using *CP* by auto
 qed

lemma *derived-S5-rules-1-a*[*PLM*]:
 assumes $\bigwedge v. [\chi \text{ in } v] \Longrightarrow [\Diamond\varphi \rightarrow \psi \text{ in } v]$
 shows $[\Box\chi \text{ in } v] \Longrightarrow [\varphi \rightarrow \Box\psi \text{ in } v]$
proof –
 have $[\Box\chi \text{ in } v] \Longrightarrow [\Box\Diamond\varphi \rightarrow \Box\psi \text{ in } v]$
 using *assms* *RM-1-b* by *metis*
 thus $[\Box\chi \text{ in } v] \Longrightarrow [\varphi \rightarrow \Box\psi \text{ in } v]$

using *S5Basic-4 vdash-properties-10 CP* by *metis*
qed

lemma *derived-S5-rules-1-b[PLM]*:
assumes $\bigwedge v. [\Diamond \varphi \rightarrow \psi \text{ in } v]$
shows $[\varphi \rightarrow \Box \psi \text{ in } v]$
using *derived-S5-rules-1-a all-self-eq-1 assms* by *blast*

lemma *derived-S5-rules-2-a[PLM]*:
assumes $\bigwedge v. [\chi \text{ in } v] \implies [\varphi \rightarrow \Box \psi \text{ in } v]$
shows $[\Box \chi \text{ in } v] \implies [\Diamond \varphi \rightarrow \psi \text{ in } v]$
proof –
have $[\Box \chi \text{ in } v] \implies [\Diamond \varphi \rightarrow \Diamond \Box \psi \text{ in } v]$
using *RM-2-b assms* by *metis*
thus $[\Box \chi \text{ in } v] \implies [\Diamond \varphi \rightarrow \psi \text{ in } v]$
using *B \Diamond vdash-properties-10 CP* by *metis*
qed

lemma *derived-S5-rules-2-b[PLM]*:
assumes $\bigwedge v. [\varphi \rightarrow \Box \psi \text{ in } v]$
shows $[\Diamond \varphi \rightarrow \psi \text{ in } v]$
using *assms derived-S5-rules-2-a all-self-eq-1* by *blast*

lemma *BFs-1[PLM]*: $[(\forall \alpha. \Box(\varphi \alpha)) \rightarrow \Box(\forall \alpha. \varphi \alpha) \text{ in } v]$
proof (*rule derived-S5-rules-1-b*)
fix v
{
 fix α
 have $\bigwedge v. [(\forall \alpha. \Box(\varphi \alpha)) \rightarrow \Box(\varphi \alpha) \text{ in } v]$
 using *cqt-orig-1* by *metis*
 hence $[\Diamond(\forall \alpha. \Box(\varphi \alpha)) \rightarrow \Diamond \Box(\varphi \alpha) \text{ in } v]$
 using *RM-2* by *metis*
 moreover have $[\Diamond \Box(\varphi \alpha) \rightarrow (\varphi \alpha) \text{ in } v]$
 using *B \Diamond* by *auto*
 ultimately have $[\Diamond(\forall \alpha. \Box(\varphi \alpha)) \rightarrow (\varphi \alpha) \text{ in } v]$
 using *ded-thm-cor-3* by *auto*
}
hence $[\forall \alpha. \Diamond(\forall \alpha. \Box(\varphi \alpha)) \rightarrow (\varphi \alpha) \text{ in } v]$
using $\forall I$ by *metis*
thus $[\Diamond(\forall \alpha. \Box(\varphi \alpha)) \rightarrow (\forall \alpha. \varphi \alpha) \text{ in } v]$
using *cqt-orig-2[deduction]* by *auto*
qed
lemmas $BF = BFs-1$

lemma *BFs-2[PLM]*:
 $[\Box(\forall \alpha. \varphi \alpha) \rightarrow (\forall \alpha. \Box(\varphi \alpha)) \text{ in } v]$
proof –
{
 fix α
 {
 fix v
 have $[(\forall \alpha. \varphi \alpha) \rightarrow \varphi \alpha \text{ in } v]$ using *cqt-orig-1* by *metis*
 }
 hence $[\Box(\forall \alpha. \varphi \alpha) \rightarrow \Box(\varphi \alpha) \text{ in } v]$ using *RM-1* by *auto*
}
hence $[\forall \alpha. \Box(\forall \alpha. \varphi \alpha) \rightarrow \Box(\varphi \alpha) \text{ in } v]$ using $\forall I$ by *metis*
thus *?thesis* using *cqt-orig-2[deduction]* by *metis*
qed
lemmas $CBF = BFs-2$

lemma *BFs-3[PLM]*:
 $[\Diamond(\exists \alpha. \varphi \alpha) \rightarrow (\exists \alpha. \Diamond(\varphi \alpha)) \text{ in } v]$
proof –


```

have [( $\forall \alpha. \Box(\neg(\varphi \alpha)) \rightarrow \Box(\forall \alpha. \neg(\varphi \alpha))$ ) in v]
  using BF by metis
hence 1: [( $\neg(\Box(\forall \alpha. \neg(\varphi \alpha))) \rightarrow (\neg(\forall \alpha. \Box(\neg(\varphi \alpha))))$ ) in v]
  using contraposition-1 by simp
have 2: [( $\Diamond(\neg(\forall \alpha. \neg(\varphi \alpha))) \rightarrow (\neg(\forall \alpha. \Box(\neg(\varphi \alpha))))$ ) in v]
  apply (PLM-subst-method  $\neg\Box(\forall \alpha. \neg(\varphi \alpha)) \Diamond(\neg(\forall \alpha. \neg(\varphi \alpha)))$ )
  using KBasic2-2 1 by simp+
have [( $\Diamond(\neg(\forall \alpha. \neg(\varphi \alpha))) \rightarrow (\exists \alpha. \neg(\Box(\neg(\varphi \alpha))))$ ) in v]
  apply (PLM-subst-method  $\neg(\forall \alpha. \Box(\neg(\varphi \alpha))) \exists \alpha. \neg(\Box(\neg(\varphi \alpha)))$ )
  using cqt-further-2 apply metis
  using 2 by metis
thus ?thesis
  unfolding exists-def diamond-def by auto
qed
lemmas BF $\Diamond = \text{BFs-3}$ 

```

lemma *BFs-4*[*PLM*]:

```

[( $\exists \alpha. \Diamond(\varphi \alpha) \rightarrow \Diamond(\exists \alpha. \varphi \alpha)$ ) in v]
proof -
  have 1: [ $\Box(\forall \alpha. \neg(\varphi \alpha)) \rightarrow (\forall \alpha. \Box(\neg(\varphi \alpha)))$ ] in v]
    using CBF by auto
  have 2: [( $\exists \alpha. (\neg(\Box(\neg(\varphi \alpha)))) \rightarrow (\neg(\Box(\forall \alpha. \neg(\varphi \alpha))))$ ) in v]
    apply (PLM-subst-method  $\neg(\forall \alpha. \Box(\neg(\varphi \alpha))) (\exists \alpha. (\neg(\Box(\neg(\varphi \alpha))))$ )
    using cqt-further-2 apply assumption
    using 1 using contraposition-1 by metis
  have [( $\exists \alpha. (\neg(\Box(\neg(\varphi \alpha)))) \rightarrow \Diamond(\neg(\forall \alpha. \neg(\varphi \alpha)))$ ) in v]
    apply (PLM-subst-method  $\neg(\Box(\forall \alpha. \neg(\varphi \alpha))) \Diamond(\neg(\forall \alpha. \neg(\varphi \alpha)))$ )
    using KBasic2-2 apply assumption
    using 2 by assumption
  thus ?thesis
    unfolding diamond-def exists-def by auto
qed
lemmas CBF $\Diamond = \text{BFs-4}$ 

```

lemma *sign-S5-thm-1*[*PLM*]:

```

[( $\exists \alpha. \Box(\varphi \alpha) \rightarrow \Box(\exists \alpha. \varphi \alpha)$ ) in v]
proof (rule CP)
  assume [ $\exists \alpha. \Box(\varphi \alpha)$ ] in v]
  then obtain  $\tau$  where [ $\Box(\varphi \tau)$ ] in v]
    by (rule  $\exists E$ )
  moreover {
    fix v
    assume [ $\varphi \tau$ ] in v]
    hence [ $\exists \alpha. \varphi \alpha$ ] in v]
      by (rule  $\exists I$ )
  }
  ultimately show [ $\Box(\exists \alpha. \varphi \alpha)$ ] in v]
    using RN-2 by blast
qed
lemmas Buridan = sign-S5-thm-1

```

lemma *sign-S5-thm-2*[*PLM*]:

```

[( $\Diamond(\forall \alpha. \varphi \alpha) \rightarrow (\forall \alpha. \Diamond(\varphi \alpha))$ ) in v]
proof -
  {
    fix  $\alpha$ 
    {
      fix v
      have [( $\forall \alpha. \varphi \alpha \rightarrow \varphi \alpha$ ) in v]
        using cqt-orig-1 by metis
    }
    hence [ $\Diamond(\forall \alpha. \varphi \alpha) \rightarrow \Diamond(\varphi \alpha)$ ] in v]
      using RM-2 by metis
  }

```

```

}
hence  $[\forall \alpha . \Diamond(\forall \alpha . \varphi \alpha) \rightarrow \Diamond(\varphi \alpha) \text{ in } v]$ 
  using  $\forall I$  by metis
thus ?thesis
  using cqt-orig-2[deduction] by metis
qed
lemmas Buridan $\Diamond = \text{sign-S5-thm-2}$ 

lemma sign-S5-thm-3[PLM]:
 $[\Diamond(\exists \alpha . \varphi \alpha \ \& \ \psi \alpha) \rightarrow \Diamond((\exists \alpha . \varphi \alpha) \ \& \ (\exists \alpha . \psi \alpha)) \text{ in } v]$ 
  by (simp only: RM-2 cqt-further-5)

lemma sign-S5-thm-4[PLM]:
 $[(\Box(\forall \alpha . \varphi \alpha \rightarrow \psi \alpha)) \ \& \ (\Box(\forall \alpha . \psi \alpha \rightarrow \chi \alpha))] \rightarrow \Box(\forall \alpha . \varphi \alpha \rightarrow \chi \alpha) \text{ in } v]$ 
  proof (rule CP)
    assume  $[\Box(\forall \alpha . \varphi \alpha \rightarrow \psi \alpha) \ \& \ \Box(\forall \alpha . \psi \alpha \rightarrow \chi \alpha) \text{ in } v]$ 
    hence  $[\Box((\forall \alpha . \varphi \alpha \rightarrow \psi \alpha) \ \& \ (\forall \alpha . \psi \alpha \rightarrow \chi \alpha)) \text{ in } v]$ 
      using KBasic-3[equiv-rl] by blast
    moreover {
      fix v
      assume  $[(\forall \alpha . \varphi \alpha \rightarrow \psi \alpha) \ \& \ (\forall \alpha . \psi \alpha \rightarrow \chi \alpha) \text{ in } v]$ 
      hence  $[(\forall \alpha . \varphi \alpha \rightarrow \chi \alpha) \text{ in } v]$ 
        using cqt-basic-9[deduction] by blast
    }
    ultimately show  $[\Box(\forall \alpha . \varphi \alpha \rightarrow \chi \alpha) \text{ in } v]$ 
      using RN-2 by blast
  qed

lemma sign-S5-thm-5[PLM]:
 $[(\Box(\forall \alpha . \varphi \alpha \equiv \psi \alpha)) \ \& \ (\Box(\forall \alpha . \psi \alpha \equiv \chi \alpha))] \rightarrow (\Box(\forall \alpha . \varphi \alpha \equiv \chi \alpha)) \text{ in } v]$ 
  proof (rule CP)
    assume  $[\Box(\forall \alpha . \varphi \alpha \equiv \psi \alpha) \ \& \ \Box(\forall \alpha . \psi \alpha \equiv \chi \alpha) \text{ in } v]$ 
    hence  $[\Box((\forall \alpha . \varphi \alpha \equiv \psi \alpha) \ \& \ (\forall \alpha . \psi \alpha \equiv \chi \alpha)) \text{ in } v]$ 
      using KBasic-3[equiv-rl] by blast
    moreover {
      fix v
      assume  $[(\forall \alpha . \varphi \alpha \equiv \psi \alpha) \ \& \ (\forall \alpha . \psi \alpha \equiv \chi \alpha) \text{ in } v]$ 
      hence  $[(\forall \alpha . \varphi \alpha \equiv \chi \alpha) \text{ in } v]$ 
        using cqt-basic-10[deduction] by blast
    }
    ultimately show  $[\Box(\forall \alpha . \varphi \alpha \equiv \chi \alpha) \text{ in } v]$ 
      using RN-2 by blast
  qed

lemma id-nec2-1[PLM]:
 $[\Diamond((\alpha::'a::id-eq) = \beta) \equiv (\alpha = \beta) \text{ in } v]$ 
  apply (rule  $\equiv I$ ; rule CP)
  using id-nec[equiv-lr] derived-S5-rules-2-b CP modus-ponens apply blast
  using T $\Diamond$ [deduction] by auto

lemma id-nec2-2-Aux:
 $[(\Diamond \varphi) \equiv \psi \text{ in } v] \implies [(\neg \psi) \equiv \Box(\neg \varphi) \text{ in } v]$ 
  proof -
    assume  $[(\Diamond \varphi) \equiv \psi \text{ in } v]$ 
    moreover have  $\bigwedge \varphi \psi. [(\neg \varphi) \equiv \psi \text{ in } v] \implies [(\neg \psi) \equiv \varphi \text{ in } v]$ 
      by PLM-solver
    ultimately show ?thesis
      unfolding diamond-def by blast
  qed

lemma id-nec2-2[PLM]:
 $[(\alpha::'a::id-eq) \neq \beta] \equiv \Box(\alpha \neq \beta) \text{ in } v]$ 
  using id-nec2-1[THEN id-nec2-2-Aux] by auto

```

lemma *id-nec2-3*[PLM]:
 $[(\Diamond((\alpha::'a::id-eq) \neq \beta)) \equiv (\alpha \neq \beta)] \text{ in } v$
using *T* $\Diamond \equiv I$ *id-nec2-2*[*equiv-lr*]
CP derived-S5-rules-2-b **by** *metis*

lemma *exists-desc-box-1*[PLM]:
 $[(\exists y. (y^P) = (\iota x. \varphi x)) \rightarrow (\exists y. \Box((y^P) = (\iota x. \varphi x))) \text{ in } v]$
proof (*rule CP*)
assume $[\exists y. (y^P) = (\iota x. \varphi x) \text{ in } v]$
then obtain *y* **where** $[(y^P) = (\iota x. \varphi x) \text{ in } v]$
by (*rule* $\exists E$)
hence $[\Box(y^P = (\iota x. \varphi x)) \text{ in } v]$
using *l-identity*[*axiom-instance*, *deduction*, *deduction*]
cqt-1[*axiom-instance*] *all-self-eq-2*[**where** '*a*=*v*]
modus-ponens **unfolding** *identity- ν -def* **by** *fast*
thus $[\exists y. \Box((y^P) = (\iota x. \varphi x)) \text{ in } v]$
by (*rule* $\exists I$)
qed

lemma *exists-desc-box-2*[PLM]:
 $[(\exists y. (y^P) = (\iota x. \varphi x)) \rightarrow \Box(\exists y. (y^P) = (\iota x. \varphi x))] \text{ in } v$
using *exists-desc-box-1* *Buridan ded-thm-cor-3* **by** *fast*

lemma *en-eq-1*[PLM]:
 $[\Diamond \llbracket x, F \rrbracket \equiv \Box \llbracket x, F \rrbracket \text{ in } v]$
using *encoding*[*axiom-instance*] *RN*
sc-eq-box-box-1 *modus-ponens* **by** *blast*

lemma *en-eq-2*[PLM]:
 $[\llbracket x, F \rrbracket \equiv \Box \llbracket x, F \rrbracket \text{ in } v]$
using *encoding*[*axiom-instance*] *qml-2*[*axiom-instance*] **by** (*rule* $\equiv I$)

lemma *en-eq-3*[PLM]:
 $[\Diamond \llbracket x, F \rrbracket \equiv \llbracket x, F \rrbracket \text{ in } v]$
using *encoding*[*axiom-instance*] *derived-S5-rules-2-b* $\equiv I$ *T* \Diamond **by** *auto*

lemma *en-eq-4*[PLM]:
 $[(\llbracket x, F \rrbracket \equiv \llbracket y, G \rrbracket) \equiv (\Box \llbracket x, F \rrbracket \equiv \Box \llbracket y, G \rrbracket) \text{ in } v]$
by (*metis* *CP en-eq-2* $\equiv I \equiv E(1) \equiv E(2)$)

lemma *en-eq-5*[PLM]:
 $[(\Box \llbracket x, F \rrbracket \equiv \llbracket y, G \rrbracket) \equiv (\Box \llbracket x, F \rrbracket \equiv \Box \llbracket y, G \rrbracket) \text{ in } v]$
using $\equiv I$ *KBasic-6* *encoding*[*axiom-necessitation*, *axiom-instance*]
sc-eq-box-box-3[*deduction*] $\&I$ **by** *simp*

lemma *en-eq-6*[PLM]:
 $[(\llbracket x, F \rrbracket \equiv \llbracket y, G \rrbracket) \equiv \Box(\llbracket x, F \rrbracket \equiv \llbracket y, G \rrbracket) \text{ in } v]$
using *en-eq-4* *en-eq-5* *oth-class-taut-4-a* $\equiv E(6)$ **by** *meson*

lemma *en-eq-7*[PLM]:
 $[(\neg \llbracket x, F \rrbracket) \equiv \Box(\neg \llbracket x, F \rrbracket) \text{ in } v]$
using *en-eq-3*[*THEN id-nec2-2-Aux*] **by** *blast*

lemma *en-eq-8*[PLM]:
 $[\Diamond(\neg \llbracket x, F \rrbracket) \equiv (\neg \llbracket x, F \rrbracket) \text{ in } v]$
unfolding *diamond-def* **apply** (*PLM-subst-method* $\llbracket x, F \rrbracket \neg \neg \llbracket x, F \rrbracket$)
using *oth-class-taut-4-b* **apply** *assumption*
apply (*PLM-subst-method* $\llbracket x, F \rrbracket \Box \llbracket x, F \rrbracket$)
using *en-eq-2* **apply** *assumption*
using *oth-class-taut-4-a* **by** *assumption*

lemma *en-eq-9*[PLM]:
 $[\Diamond(\neg \llbracket x, F \rrbracket) \equiv \Box(\neg \llbracket x, F \rrbracket) \text{ in } v]$
using *en-eq-8* *en-eq-7* $\equiv E(5)$ **by** *blast*

lemma *en-eq-10*[PLM]:
 $[\mathcal{A} \llbracket x, F \rrbracket \equiv \llbracket x, F \rrbracket \text{ in } v]$
apply (*rule* $\equiv I$)
using *encoding*[*axiom-actualization*, *axiom-instance*,
THEN logic-actual-nec-2[*axiom-instance*, *equiv-lr*],
deduction, *THEN qml-act-2*[*axiom-instance*, *equiv-rl*],

THEN en-eq-2[equiv-rl]] CP

apply *simp*
using *encoding[axiom-instance] nec-imp-act ded-thm-cor-3* **by** *blast*

9.11 The Theory of Relations

lemma *beta-equiv-eq-1-1[PLM]*:
assumes *IsPropositionalInX* φ
and *IsPropositionalInX* ψ
and $\bigwedge x. [\varphi(x^P) \equiv \psi(x^P) \text{ in } v]$
shows $[(\lambda y. \varphi(y^P), x^P) \equiv (\lambda y. \psi(y^P), x^P) \text{ in } v]$
using *lambda-predicates-2-1[OF assms(1), axiom-instance]*
using *lambda-predicates-2-1[OF assms(2), axiom-instance]*
using *assms(3)* **by** (*meson* $\equiv E(6)$ *oth-class-taut-4-a*)

lemma *beta-equiv-eq-1-2[PLM]*:
assumes *IsPropositionalInXY* φ
and *IsPropositionalInXY* ψ
and $\bigwedge x y. [\varphi(x^P)(y^P) \equiv \psi(x^P)(y^P) \text{ in } v]$
shows $[(\lambda^2(\lambda x y. \varphi(x^P)(y^P)), x^P, y^P) \equiv (\lambda^2(\lambda x y. \psi(x^P)(y^P)), x^P, y^P) \text{ in } v]$
using *lambda-predicates-2-2[OF assms(1), axiom-instance]*
using *lambda-predicates-2-2[OF assms(2), axiom-instance]*
using *assms(3)* **by** (*meson* $\equiv E(6)$ *oth-class-taut-4-a*)

lemma *beta-equiv-eq-1-3[PLM]*:
assumes *IsPropositionalInXYZ* φ
and *IsPropositionalInXYZ* ψ
and $\bigwedge x y z. [\varphi(x^P)(y^P)(z^P) \equiv \psi(x^P)(y^P)(z^P) \text{ in } v]$
shows $[(\lambda^3(\lambda x y z. \varphi(x^P)(y^P)(z^P)), x^P, y^P, z^P) \equiv (\lambda^3(\lambda x y z. \psi(x^P)(y^P)(z^P)), x^P, y^P, z^P) \text{ in } v]$
using *lambda-predicates-2-3[OF assms(1), axiom-instance]*
using *lambda-predicates-2-3[OF assms(2), axiom-instance]*
using *assms(3)* **by** (*meson* $\equiv E(6)$ *oth-class-taut-4-a*)

lemma *beta-equiv-eq-2-1[PLM]*:
assumes *IsPropositionalInX* φ
and *IsPropositionalInX* ψ
shows $[(\Box(\forall x. \varphi(x^P) \equiv \psi(x^P))) \rightarrow (\Box(\forall x. (\lambda y. \varphi(y^P), x^P) \equiv (\lambda y. \psi(y^P), x^P))) \text{ in } v]$
apply (*rule qml-1[axiom-instance, deduction]*)
apply (*rule RN*)
proof (*rule CP, rule* $\forall I$)
fix $v x$
assume $[\forall x. \varphi(x^P) \equiv \psi(x^P) \text{ in } v]$
hence $\bigwedge x. [\varphi(x^P) \equiv \psi(x^P) \text{ in } v]$
by *PLM-solver*
thus $[(\lambda y. \varphi(y^P), x^P) \equiv (\lambda y. \psi(y^P), x^P) \text{ in } v]$
using *assms beta-equiv-eq-1-1* **by** *auto*
qed

lemma *beta-equiv-eq-2-2[PLM]*:
assumes *IsPropositionalInXY* φ
and *IsPropositionalInXY* ψ
shows $[(\Box(\forall x y. \varphi(x^P)(y^P) \equiv \psi(x^P)(y^P))) \rightarrow (\Box(\forall x y. (\lambda^2(\lambda x y. \varphi(x^P)(y^P)), x^P, y^P) \equiv (\lambda^2(\lambda x y. \psi(x^P)(y^P)), x^P, y^P))) \text{ in } v]$
apply (*rule qml-1[axiom-instance, deduction]*)
apply (*rule RN*)
proof (*rule CP, rule* $\forall I$, *rule* $\forall I$)
fix $v x y$
assume $[\forall x y. \varphi(x^P)(y^P) \equiv \psi(x^P)(y^P) \text{ in } v]$
hence $(\bigwedge x y. [\varphi(x^P)(y^P) \equiv \psi(x^P)(y^P) \text{ in } v])$

by (*meson* $\forall E$)
 thus $[(\lambda^2 (\lambda x y. \varphi (x^P) (y^P)), x^P, y^P) \equiv (\lambda^2 (\lambda x y. \psi (x^P) (y^P)), x^P, y^P)]$ in v
 using *assms beta-equiv-eq-1-2* by *auto*
 qed

lemma *beta-equiv-eq-2-3*[*PLM*]:
 assumes *IsPropositionalInXYZ* φ
 and *IsPropositionalInXYZ* ψ
 shows $[(\Box(\forall x y z. \varphi (x^P) (y^P) (z^P)) \equiv \psi (x^P) (y^P) (z^P)) \rightarrow (\Box(\forall x y z. (\lambda^3 (\lambda x y z. \varphi (x^P) (y^P) (z^P)), x^P, y^P, z^P) \equiv (\lambda^3 (\lambda x y z. \psi (x^P) (y^P) (z^P)), x^P, y^P, z^P))] in v$
 apply (*rule qml-1*[*axiom-instance*, *deduction*])
 apply (*rule RN*)
 proof (*rule CP*, *rule* $\forall I$, *rule* $\forall I$, *rule* $\forall I$)
 fix $v x y z$
 assume $[\forall x y z. \varphi (x^P) (y^P) (z^P) \equiv \psi (x^P) (y^P) (z^P)]$ in v
 hence $[\bigwedge x y z. [\varphi (x^P) (y^P) (z^P) \equiv \psi (x^P) (y^P) (z^P)]]$ in v
 by (*meson* $\forall E$)
 thus $[(\lambda^3 (\lambda x y z. \varphi (x^P) (y^P) (z^P)), x^P, y^P, z^P) \equiv (\lambda^3 (\lambda x y z. \psi (x^P) (y^P) (z^P)), x^P, y^P, z^P)]$ in v
 using *assms beta-equiv-eq-1-3* by *auto*
 qed

lemma *beta-C-meta-1*[*PLM*]:
 assumes *IsPropositionalInX* φ
 shows $[(\lambda y. \varphi (y^P), x^P) \equiv \varphi (x^P)]$ in v
 using *lambda-predicates-2-1*[*OF assms*, *axiom-instance*] by *auto*

lemma *beta-C-meta-2*[*PLM*]:
 assumes *IsPropositionalInXY* φ
 shows $[(\lambda^2 (\lambda x y. \varphi (x^P) (y^P)), x^P, y^P) \equiv \varphi (x^P) (y^P)]$ in v
 using *lambda-predicates-2-2*[*OF assms*, *axiom-instance*] by *auto*

lemma *beta-C-meta-3*[*PLM*]:
 assumes *IsPropositionalInXYZ* φ
 shows $[(\lambda^3 (\lambda x y z. \varphi (x^P) (y^P) (z^P)), x^P, y^P, z^P) \equiv \varphi (x^P) (y^P) (z^P)]$ in v
 using *lambda-predicates-2-3*[*OF assms*, *axiom-instance*] by *auto*

lemma *relations-1*[*PLM*]:
 assumes *IsPropositionalInX* φ
 shows $[\exists F. \Box(\forall x. (F, x^P) \equiv \varphi (x^P))] in v$
 using *assms* apply *cut-tac* by *PLM-solver*

lemma *relations-2*[*PLM*]:
 assumes *IsPropositionalInXY* φ
 shows $[\exists F. \Box(\forall x y. (F, x^P, y^P) \equiv \varphi (x^P) (y^P))] in v$
 using *assms* apply *cut-tac* by *PLM-solver*

lemma *relations-3*[*PLM*]:
 assumes *IsPropositionalInXYZ* φ
 shows $[\exists F. \Box(\forall x y z. (F, x^P, y^P, z^P) \equiv \varphi (x^P) (y^P) (z^P))] in v$
 using *assms* apply *cut-tac* by *PLM-solver*

lemma *prop-equiv*[*PLM*]:
 shows $[(\forall x. (\{x^P, F\} \equiv \{x^P, G\})) \rightarrow F = G] in v$
 proof (*rule CP*)
 assume $1: [\forall x. \{x^P, F\} \equiv \{x^P, G\}] in v$
 {
 fix x
 have $[\{x^P, F\} \equiv \{x^P, G\}] in v$
 using 1 by (*rule* $\forall E$)
 hence $[\Box(\{x^P, F\} \equiv \{x^P, G\})] in v$

```

    using PLM.en-eq-6  $\equiv E(1)$  by blast
  }
  hence  $[\forall x. \Box(\llbracket x^P, F \rrbracket \equiv \llbracket x^P, G \rrbracket) \text{ in } v]$ 
    by (rule  $\forall I$ )
  thus  $[F = G \text{ in } v]$ 
    unfolding identity-defs
    by (rule BF[deduction])
qed

```

lemma *propositions-lemma-1*[PLM]:

```

 $[\lambda^0 \varphi = \varphi \text{ in } v]$ 
using lambda-predicates-3-0[axiom-instance] .

```

lemma *propositions-lemma-2*[PLM]:

```

 $[\lambda^0 \varphi \equiv \varphi \text{ in } v]$ 
using lambda-predicates-3-0[axiom-instance, THEN id-eq-prop-prop-8-b[deduction]]
apply (rule l-identity[axiom-instance, deduction, deduction])
by PLM-solver

```

lemma *propositions-lemma-4*[PLM]:

```

assumes  $\bigwedge x. [\mathcal{A}(\varphi x \equiv \psi x) \text{ in } v]$ 
shows  $[(\chi :: \kappa \Rightarrow o) (\iota x. \varphi x) = \chi (\iota x. \psi x) \text{ in } v]$ 
proof -
  have  $[\lambda^0 (\chi (\iota x. \varphi x)) = \lambda^0 (\chi (\iota x. \psi x)) \text{ in } v]$ 
    using assms lambda-predicates-4-0
    by blast
  hence  $[(\chi (\iota x. \varphi x)) = \lambda^0 (\chi (\iota x. \psi x)) \text{ in } v]$ 
    using propositions-lemma-1[THEN id-eq-prop-prop-8-b[deduction]]
    id-eq-prop-prop-9-b[deduction] &I
    by blast
  thus ?thesis
    using propositions-lemma-1 id-eq-prop-prop-9-b[deduction] &I
    by blast
qed

```

TODO 1. *Remark 132?*

lemma *propositions*[PLM]:

```

 $[\exists p. \Box(p \equiv p') \text{ in } v]$ 
by PLM-solver

```

lemma *pos-not-equiv-then-not-eq*[PLM]:

```

 $[\Diamond(\neg(\forall x. (\llbracket F, x^P \rrbracket \equiv \llbracket G, x^P \rrbracket))) \rightarrow F \neq G \text{ in } v]$ 
unfolding diamond-def
proof (subst contraposition-1[symmetric], rule CP)
  assume  $[F = G \text{ in } v]$ 
  thus  $[\Box(\neg(\neg(\forall x. (\llbracket F, x^P \rrbracket \equiv \llbracket G, x^P \rrbracket)))) \text{ in } v]$ 
    apply (rule l-identity[axiom-instance, deduction, deduction])
    by PLM-solver
qed

```

lemma *thm-relation-negation-1-1*[PLM]:

```

 $[(\llbracket F^-, x^P \rrbracket \equiv \neg(\llbracket F, x^P \rrbracket) \text{ in } v]$ 
unfolding propnot-defs
apply (rule lambda-predicates-2-1[axiom-instance])
by (rule IsPropositional-intros)+

```

lemma *thm-relation-negation-1-2*[PLM]:

```

 $[(\llbracket F^-, x^P, y^P \rrbracket \equiv \neg(\llbracket F, x^P, y^P \rrbracket) \text{ in } v]$ 
unfolding propnot-defs
apply (rule lambda-predicates-2-2[axiom-instance])
by (rule IsPropositional-intros)+

```

lemma *thm-relation-negation-1-3*[PLM]:

$[(\neg(F^-, x^P, y^P, z^P)) \equiv \neg(F, x^P, y^P, z^P)] \text{ in } v]$
unfolding *propnot-defs*
apply (*rule lambda-predicates-2-3*[*axiom-instance*])
by (*rule IsPropositional-intros*)+

lemma *thm-relation-negation-2-1*[*PLM*]:
 $[(\neg(\neg(F^-, x^P))) \equiv (F, x^P)] \text{ in } v]$
using *thm-relation-negation-1-1*[*THEN oth-class-taut-5-d*[*equiv-lr*]]
apply *cut-tac* **by** *PLM-solver*

lemma *thm-relation-negation-2-2*[*PLM*]:
 $[(\neg(\neg(F^-, x^P, y^P))) \equiv (F, x^P, y^P)] \text{ in } v]$
using *thm-relation-negation-1-2*[*THEN oth-class-taut-5-d*[*equiv-lr*]]
apply *cut-tac* **by** *PLM-solver*

lemma *thm-relation-negation-2-3*[*PLM*]:
 $[(\neg(\neg(F^-, x^P, y^P, z^P))) \equiv (F, x^P, y^P, z^P)] \text{ in } v]$
using *thm-relation-negation-1-3*[*THEN oth-class-taut-5-d*[*equiv-lr*]]
apply *cut-tac* **by** *PLM-solver*

lemma *thm-relation-negation-3*[*PLM*]:
 $[(p)^- \equiv \neg p] \text{ in } v]$
unfolding *propnot-defs*
using *propositions-lemma-2* **by** *simp*

lemma *thm-relation-negation-4*[*PLM*]:
 $[(\neg((p::o)^-)) \equiv p] \text{ in } v]$
using *thm-relation-negation-3*[*THEN oth-class-taut-5-d*[*equiv-lr*]]
apply *cut-tac* **by** *PLM-solver*

lemma *thm-relation-negation-5-1*[*PLM*]:
 $[(F::\Pi_1) \neq (F^-)] \text{ in } v]$
using *id-eq-prop-prop-2*[*deduction*]
l-identity[**where** $\varphi = \lambda G . (G, x^P) \equiv (F^-, x^P)$, *axiom-instance*,
deduction, *deduction*]
oth-class-taut-4-a *thm-relation-negation-1-1* $\equiv E(5)$
oth-class-taut-1-b *modus-tollens-1* *CP*
by *meson*

lemma *thm-relation-negation-5-2*[*PLM*]:
 $[(F::\Pi_2) \neq (F^-)] \text{ in } v]$
using *id-eq-prop-prop-5-a*[*deduction*]
l-identity[**where** $\varphi = \lambda G . (G, x^P, y^P) \equiv (F^-, x^P, y^P)$, *axiom-instance*,
deduction, *deduction*]
oth-class-taut-4-a *thm-relation-negation-1-2* $\equiv E(5)$
oth-class-taut-1-b *modus-tollens-1* *CP*
by *meson*

lemma *thm-relation-negation-5-3*[*PLM*]:
 $[(F::\Pi_3) \neq (F^-)] \text{ in } v]$
using *id-eq-prop-prop-5-b*[*deduction*]
l-identity[**where** $\varphi = \lambda G . (G, x^P, y^P, z^P) \equiv (F^-, x^P, y^P, z^P)$,
axiom-instance, *deduction*, *deduction*]
oth-class-taut-4-a *thm-relation-negation-1-3* $\equiv E(5)$
oth-class-taut-1-b *modus-tollens-1* *CP*
by *meson*

lemma *thm-relation-negation-6*[*PLM*]:
 $[(p::o) \neq (p^-)] \text{ in } v]$
using *id-eq-prop-prop-8-b*[*deduction*]
l-identity[**where** $\varphi = \lambda G . G \equiv (p^-)$, *axiom-instance*,
deduction, *deduction*]
oth-class-taut-4-a *thm-relation-negation-3* $\equiv E(5)$

oth-class-taut-1-b modus-tollens-1 CP
by meson

lemma *thm-relation-negation-7[PLM]*:
 $[(p::o)^-] = \neg p$ in v
unfolding *propnot-defs* **using** *propositions-lemma-1* **by simp**

lemma *thm-relation-negation-8[PLM]*:
 $(p::o) \neq \neg p$ in v
unfolding *propnot-defs*
using *id-eq-prop-prop-8-b[deduction]*
 l -identity[**where** $\varphi=\lambda G . G \equiv \neg(p)$, *axiom-instance*,
deduction, *deduction*]
oth-class-taut-4-a oth-class-taut-1-b
modus-tollens-1 CP
by meson

lemma *thm-relation-negation-9[PLM]*:
 $[(p::o) = q] \rightarrow ((\neg p) = (\neg q))$ in v
using l -identity[**where** $\alpha=p$ **and** $\beta=q$ **and** $\varphi=\lambda x . (\neg p) = (\neg x)$,
axiom-instance, *deduction*]
id-eq-prop-prop-7-b **using** *CP modus-ponens* **by blast**

lemma *thm-relation-negation-10[PLM]*:
 $[(p::o) = q] \rightarrow ((p^-) = (q^-))$ in v
using l -identity[**where** $\alpha=p$ **and** $\beta=q$ **and** $\varphi=\lambda x . (p^-) = (x^-)$,
axiom-instance, *deduction*]
id-eq-prop-prop-7-b **using** *CP modus-ponens* **by blast**

lemma *thm-cont-prop-1[PLM]*:
 $[NonContingent (F::\Pi_1) \equiv NonContingent (F^-)]$ in v
proof (*rule* $\equiv I$; *rule CP*)
assume $[NonContingent F]$ in v
hence $[\Box(\forall x. \langle F, x^P \rangle) \vee \Box(\forall x. \neg \langle F, x^P \rangle)]$ in v
unfolding *NonContingent-def Necessary-defs Impossible-defs* .
hence $[\Box(\forall x. \neg \langle F^-, x^P \rangle) \vee \Box(\forall x. \neg \langle F, x^P \rangle)]$ in v
apply *cut-tac*
apply (*PLM-subst1-method* $\lambda x . \langle F, x^P \rangle \lambda x . \neg \langle F^-, x^P \rangle$)
using *thm-relation-negation-2-1[equiv-sym]* **by auto**
hence $[\Box(\forall x. \neg \langle F^-, x^P \rangle) \vee \Box(\forall x. \langle F^-, x^P \rangle)]$ in v
apply *cut-tac*
apply (*PLM-subst1-goal-method* $\lambda \varphi . \Box(\forall x. \neg \langle F^-, x^P \rangle) \vee \Box(\forall x. \varphi x) \lambda x . \neg \langle F, x^P \rangle$)
using *thm-relation-negation-1-1[equiv-sym]* **by auto**
hence $[\Box(\forall x. \langle F^-, x^P \rangle) \vee \Box(\forall x. \neg \langle F^-, x^P \rangle)]$ in v
by (*rule oth-class-taut-3-e[equiv-lr]*)
thus $[NonContingent (F^-)]$ in v
unfolding *NonContingent-def Necessary-defs Impossible-defs* .
next
assume $[NonContingent (F^-)]$ in v
hence $[\Box(\forall x. \neg \langle F^-, x^P \rangle) \vee \Box(\forall x. \langle F^-, x^P \rangle)]$ in v
unfolding *NonContingent-def Necessary-defs Impossible-defs*
by (*rule oth-class-taut-3-e[equiv-lr]*)
hence $[\Box(\forall x. \langle F, x^P \rangle) \vee \Box(\forall x. \neg \langle F^-, x^P \rangle)]$ in v
apply *cut-tac*
apply (*PLM-subst1-method* $\lambda x . \neg \langle F^-, x^P \rangle \lambda x . \langle F, x^P \rangle$)
using *thm-relation-negation-2-1* **by auto**
hence $[\Box(\forall x. \langle F, x^P \rangle) \vee \Box(\forall x. \neg \langle F, x^P \rangle)]$ in v
apply *cut-tac*
apply (*PLM-subst1-method* $\lambda x . \langle F^-, x^P \rangle \lambda x . \neg \langle F, x^P \rangle$)
using *thm-relation-negation-1-1* **by auto**
thus $[NonContingent F]$ in v
unfolding *NonContingent-def Necessary-defs Impossible-defs* .

qed

lemma *thm-cont-prop-2*[PLM]:
 $[Contingent\ F \equiv \Diamond(\exists\ x.\ \Box(F, x^P)) \ \&\ \Diamond(\exists\ x.\ \neg\Box(F, x^P))\ in\ v]$
proof (*rule* $\equiv I$; *rule* *CP*)
 assume $[Contingent\ F\ in\ v]$
 hence $[\neg(\Box(\forall\ x.\ \Box(F, x^P))) \vee \Box(\forall\ x.\ \neg\Box(F, x^P))] in\ v]$
 unfolding *Contingent-def Necessary-defs Impossible-defs* .
 hence $[(\neg\Box(\forall\ x.\ \Box(F, x^P))) \ \&\ (\neg\Box(\forall\ x.\ \neg\Box(F, x^P)))] in\ v]$
 by (*rule* *oth-class-taut-6-d*[*equiv-lr*])
 hence $[(\Diamond\neg(\forall\ x.\ \neg\Box(F, x^P))) \ \&\ (\Diamond\neg(\forall\ x.\ \Box(F, x^P)))] in\ v]$
 using *KBasic2-2*[*equiv-lr*] **&I** **&E** **by** *meson*
thus $[(\Diamond(\exists\ x.\ \Box(F, x^P))) \ \&\ (\Diamond(\exists\ x.\ \neg\Box(F, x^P)))] in\ v]$
 unfolding *exists-def* **apply** *cut-tac*
 apply (*PLM-subst1-method* $\lambda\ x.\ \Box(F, x^P)\ \lambda\ x.\ \neg\Box(F, x^P)$)
 using *oth-class-taut-4-b* **by** *auto*
next
 assume $[(\Diamond(\exists\ x.\ \Box(F, x^P))) \ \&\ (\Diamond(\exists\ x.\ \neg\Box(F, x^P)))] in\ v]$
 hence $[(\Diamond\neg(\forall\ x.\ \neg\Box(F, x^P))) \ \&\ (\Diamond\neg(\forall\ x.\ \Box(F, x^P)))] in\ v]$
 unfolding *exists-def* **apply** *cut-tac*
 apply (*PLM-subst1-goal-method*
 $\lambda\ \varphi.\ (\Diamond\neg(\forall\ x.\ \neg\Box(F, x^P))) \ \&\ (\Diamond\neg(\forall\ x.\ \varphi\ x))\ \lambda\ x.\ \neg\Box(F, x^P)$)
 using *oth-class-taut-4-b*[*equiv-sym*] **by** *auto*
 hence $[(\neg\Box(\forall\ x.\ \Box(F, x^P))) \ \&\ (\neg\Box(\forall\ x.\ \neg\Box(F, x^P)))] in\ v]$
 using *KBasic2-2*[*equiv-rl*] **&I** **&E** **by** *meson*
 hence $[\neg(\Box(\forall\ x.\ \Box(F, x^P))) \vee \Box(\forall\ x.\ \neg\Box(F, x^P))] in\ v]$
 by (*rule* *oth-class-taut-6-d*[*equiv-rl*])
thus $[Contingent\ F\ in\ v]$
 unfolding *Contingent-def Necessary-defs Impossible-defs* .
qed

lemma *thm-cont-prop-3*[PLM]:
 $[Contingent\ (F::\Pi_1) \equiv Contingent\ (F^-)\ in\ v]$
using *thm-cont-prop-1*
unfolding *NonContingent-def Contingent-def*
by (*rule* *oth-class-taut-5-d*[*equiv-lr*])

lemma *lem-cont-e*[PLM]:
 $[\Diamond(\exists\ x.\ \Box(F, x^P) \ \&\ (\Diamond\neg\Box(F, x^P))) \equiv \Diamond(\exists\ x.\ ((\neg\Box(F, x^P)) \ \&\ \Diamond\Box(F, x^P)))\ in\ v]$
proof –
 have $[\Diamond(\exists\ x.\ \Box(F, x^P) \ \&\ (\Diamond\neg\Box(F, x^P)))\ in\ v]$
 $= [\Diamond(\exists\ x.\ \Diamond(\Box(F, x^P) \ \&\ \Diamond\neg\Box(F, x^P)))\ in\ v]$
 using *BF* \Diamond [*deduction*] *CBF* \Diamond [*deduction*] **by** *fast*
also have $\dots = [\exists\ x.\ (\Diamond\Box(F, x^P) \ \&\ \Diamond\neg\Box(F, x^P))]\ in\ v]$
 apply (*PLM-subst1-method*
 $\lambda\ x.\ \Diamond(\Box(F, x^P) \ \&\ \Diamond\neg\Box(F, x^P))$
 $\lambda\ x.\ \Diamond\Box(F, x^P) \ \&\ \Diamond\neg\Box(F, x^P)$)
 using *S5Basic-12* **by** *auto*
also have $\dots = [\exists\ x.\ \Diamond\neg\Box(F, x^P) \ \&\ \Diamond\Box(F, x^P)]\ in\ v]$
 apply (*PLM-subst1-method*
 $\lambda\ x.\ \Diamond\Box(F, x^P) \ \&\ \Diamond\neg\Box(F, x^P)$
 $\lambda\ x.\ \Diamond\neg\Box(F, x^P) \ \&\ \Diamond\Box(F, x^P)$)
 using *oth-class-taut-3-b* **by** *auto*
also have $\dots = [\exists\ x.\ \Diamond((\neg\Box(F, x^P)) \ \&\ \Diamond\Box(F, x^P))]\ in\ v]$
 apply (*PLM-subst1-method*
 $\lambda\ x.\ \Diamond(\neg\Box(F, x^P)) \ \&\ \Diamond\Box(F, x^P)$
 $\lambda\ x.\ \Diamond((\neg\Box(F, x^P)) \ \&\ \Diamond\Box(F, x^P))$)
 using *S5Basic-12*[*equiv-sym*] **by** *auto*
also have $\dots = [\Diamond(\exists\ x.\ ((\neg\Box(F, x^P)) \ \&\ \Diamond\Box(F, x^P)))]\ in\ v]$
 using *CBF* \Diamond [*deduction*] *BF* \Diamond [*deduction*] **by** *fast*
finally show *?thesis* **using** $\equiv I$ *CP* **by** *blast*
qed

lemma *lem-cont-e-2*[PLM]:
 $[\Diamond(\exists x . (\Diamond(F, x^P) \ \& \ \Diamond(\neg(\Diamond(F, x^P)))) \equiv \Diamond(\exists x . (\Diamond(F^-, x^P) \ \& \ \Diamond(\neg(\Diamond(F^-, x^P)))) \text{ in } v]$
apply (*PLM-subst1-method* $\lambda x . (\Diamond(F, x^P) \ \lambda x . \neg(\Diamond(F^-, x^P)))$)
using *thm-relation-negation-2-1*[*equiv-sym*] **apply** *simp*
apply (*PLM-subst1-method* $\lambda x . \neg(\Diamond(F, x^P) \ \lambda x . (\Diamond(F^-, x^P)))$)
using *thm-relation-negation-1-1*[*equiv-sym*] **apply** *simp*
using *lem-cont-e* **by** *simp*

lemma *thm-cont-e-1*[PLM]:
 $[\Diamond(\exists x . ((\neg(\Diamond(E!, x^P)) \ \& \ (\Diamond(\Diamond(E!, x^P)))) \text{ in } v]$
using *lem-cont-e*[**where** $F=E!$, *equiv-lr*] *qml-4*[*axiom-instance*, *conj1*]
by *blast*

lemma *thm-cont-e-2*[PLM]:
 $[Contingent(E!) \text{ in } v]$
using *thm-cont-prop-2*[*equiv-rl*] $\&I$ *qml-4*[*axiom-instance*, *conj1*]
KBasic2-8[*deduction*, *OF sign-S5-thm-3*[*deduction*], *conj1*]
KBasic2-8[*deduction*, *OF sign-S5-thm-3*[*deduction*, *OF thm-cont-e-1*], *conj1*]
by *fast*

lemma *thm-cont-e-3*[PLM]:
 $[Contingent(E!^-) \text{ in } v]$
using *thm-cont-e-2* *thm-cont-prop-3*[*equiv-lr*] **by** *blast*

lemma *thm-cont-e-4*[PLM]:
 $[\exists (F::\Pi_1) G . (F \neq G \ \& \ Contingent F \ \& \ Contingent G) \text{ in } v]$
apply (*rule-tac* $\alpha=E!$ **in** $\exists I$, *rule-tac* $\alpha=E!^-$ **in** $\exists I$)
using *thm-cont-e-2* *thm-cont-e-3* *thm-relation-negation-5-1* $\&I$ **by** *auto*

context
begin
qualified definition *L* **where** $L \equiv (\lambda x . (\Diamond(E!, x^P) \rightarrow (\Diamond(E!, x^P)))$

lemma *thm-noncont-e-e-1*[PLM]:
 $[Necessary L \text{ in } v]$
unfolding *Necessary-defs L-def* **apply** (*rule RN*, *rule* $\forall I$)
apply (*rule lambda-predicates-2-1*[*axiom-instance*, *equiv-rl*])
apply (*rule IsPropositional-intros*) +
using *if-p-then-p* .

lemma *thm-noncont-e-e-2*[PLM]:
 $[Impossible(L^-) \text{ in } v]$
unfolding *Impossible-defs L-def* **apply** (*rule RN*, *rule* $\forall I$)
apply (*rule thm-relation-negation-2-1*[*equiv-rl*])
apply (*rule lambda-predicates-2-1*[*axiom-instance*, *equiv-rl*])
apply (*rule IsPropositional-intros*) +
using *if-p-then-p* .

lemma *thm-noncont-e-e-3*[PLM]:
 $[NonContingent(L) \text{ in } v]$
unfolding *NonContingent-def* **using** *thm-noncont-e-e-1*
by (*rule* $\forall I(1)$)

lemma *thm-noncont-e-e-4*[PLM]:
 $[NonContingent(L^-) \text{ in } v]$
unfolding *NonContingent-def* **using** *thm-noncont-e-e-2*
by (*rule* $\forall I(2)$)

lemma *thm-noncont-e-e-5*[PLM]:
 $[\exists (F::\Pi_1) G . F \neq G \ \& \ NonContingent F \ \& \ NonContingent G \text{ in } v]$
apply (*rule-tac* $\alpha=L$ **in** $\exists I$, *rule-tac* $\alpha=L^-$ **in** $\exists I$)
using $\exists I$ *thm-relation-negation-5-1* *thm-noncont-e-e-3*
thm-noncont-e-e-4 $\&I$

by *simp*

lemma *four-distinct-1*[PLM]:
 $[NonContingent (F::\Pi_1) \rightarrow \neg(\exists G . (Contingent G \ \& \ G = F)) \text{ in } v]$
proof (rule *CP*)
 assume $[NonContingent F \text{ in } v]$
 hence $[\neg(Contingent F) \text{ in } v]$
 unfolding *NonContingent-def Contingent-def*
 apply *cut-tac* by *PLM-solver*
 moreover {
 assume $[\exists G . Contingent G \ \& \ G = F \text{ in } v]$
 then obtain P **where** $[Contingent P \ \& \ P = F \text{ in } v]$
 by (rule $\exists E$)
 hence $[Contingent F \text{ in } v]$
 using $\&E$ *l-identity*[*axiom-instance, deduction, deduction*]
 by *blast*
 }
ultimately show $[\neg(\exists G . Contingent G \ \& \ G = F) \text{ in } v]$
using *modus-tollens-1 CP* by *blast*
qed

lemma *four-distinct-2*[PLM]:
 $[Contingent (F::\Pi_1) \rightarrow \neg(\exists G . (NonContingent G \ \& \ G = F)) \text{ in } v]$
proof (rule *CP*)
 assume $[Contingent F \text{ in } v]$
 hence $[\neg(NonContingent F) \text{ in } v]$
 unfolding *NonContingent-def Contingent-def*
 apply *cut-tac* by *PLM-solver*
 moreover {
 assume $[\exists G . NonContingent G \ \& \ G = F \text{ in } v]$
 then obtain P **where** $[NonContingent P \ \& \ P = F \text{ in } v]$
 by (rule $\exists E$)
 hence $[NonContingent F \text{ in } v]$
 using $\&E$ *l-identity*[*axiom-instance, deduction, deduction*]
 by *blast*
 }
ultimately show $[\neg(\exists G . NonContingent G \ \& \ G = F) \text{ in } v]$
using *modus-tollens-1 CP* by *blast*
qed

lemma *four-distinct-3*[PLM]:
 $[L \neq (L^-) \ \& \ L \neq E! \ \& \ L \neq (E!^-) \ \& \ (L^-) \neq E!$
 $\ \& \ (L^-) \neq (E!^-) \ \& \ E! \neq (E!^-) \text{ in } v]$
proof (rule $\&I$)
show $[L \neq (L^-) \text{ in } v]$
 by (rule *thm-relation-negation-5-1*)
next
 {
 assume $[L = E! \text{ in } v]$
 hence $[NonContingent L \ \& \ L = E! \text{ in } v]$
 using *thm-noncont-e-e-3 &I* by *auto*
 hence $[\exists G . NonContingent G \ \& \ G = E! \text{ in } v]$
 using *thm-noncont-e-e-3 &I* $\exists I$ by *fast*
 }
thus $[L \neq E! \text{ in } v]$
using *four-distinct-2*[*deduction, OF thm-cont-e-2*]
 modus-tollens-1 CP
 by *blast*
next
 {
 assume $[L = (E!^-) \text{ in } v]$
 hence $[NonContingent L \ \& \ L = (E!^-) \text{ in } v]$

```

    using thm-noncont-e-e-3 &I by auto
  hence  $\exists G . \text{NonContingent } G \ \& \ G = (E!)^- \text{ in } v$ 
    using thm-noncont-e-e-3 &I  $\exists I$  by fast
}
thus  $[L \neq (E!)^- \text{ in } v]$ 
  using four-distinct-2[deduction, OF thm-cont-e-3]
    modus-tollens-1 CP
  by blast
next
{
  assume  $[(L^-) = E! \text{ in } v]$ 
  hence  $[\text{NonContingent } (L^-) \ \& \ (L^-) = E! \text{ in } v]$ 
    using thm-noncont-e-e-4 &I by auto
  hence  $\exists G . \text{NonContingent } G \ \& \ G = E! \text{ in } v$ 
    using thm-noncont-e-e-3 &I  $\exists I$  by fast
}
thus  $[(L^-) \neq E! \text{ in } v]$ 
  using four-distinct-2[deduction, OF thm-cont-e-2]
    modus-tollens-1 CP
  by blast
next
{
  assume  $[(L^-) = (E!)^- \text{ in } v]$ 
  hence  $[\text{NonContingent } (L^-) \ \& \ (L^-) = (E!)^- \text{ in } v]$ 
    using thm-noncont-e-e-4 &I by auto
  hence  $\exists G . \text{NonContingent } G \ \& \ G = (E!)^- \text{ in } v$ 
    using thm-noncont-e-e-3 &I  $\exists I$  by fast
}
thus  $[(L^-) \neq (E!)^- \text{ in } v]$ 
  using four-distinct-2[deduction, OF thm-cont-e-3]
    modus-tollens-1 CP
  by blast
next
show  $[E! \neq (E!)^- \text{ in } v]$ 
  by (rule thm-relation-negation-5-1)
qed
end

lemma thm-cont-propos-1[PLM]:
 $[\text{NonContingent } (p::o) \equiv \text{NonContingent } (p^-) \text{ in } v]$ 
proof (rule  $\equiv I$ ; rule CP)
  assume  $[\text{NonContingent } p \text{ in } v]$ 
  hence  $[\Box p \vee \Box \neg p \text{ in } v]$ 
    unfolding NonContingent-def Necessary-defs Impossible-defs .
  hence  $[\Box(\neg(p^-)) \vee \Box(\neg p) \text{ in } v]$ 
    apply cut-tac
    apply (PLM-subst-method  $p \neg(p^-)$ )
    using thm-relation-negation-4[equiv-sym] by auto
  hence  $[\Box(\neg(p^-)) \vee \Box(p^-) \text{ in } v]$ 
    apply cut-tac
    apply (PLM-subst-goal-method  $\lambda\varphi . \Box(\neg(p^-)) \vee \Box(\varphi) \neg p$ )
    using thm-relation-negation-3[equiv-sym] by auto
  hence  $[\Box(p^-) \vee \Box(\neg(p^-)) \text{ in } v]$ 
    by (rule oth-class-taut-3-e[equiv-lr])
  thus  $[\text{NonContingent } (p^-) \text{ in } v]$ 
    unfolding NonContingent-def Necessary-defs Impossible-defs .
next
  assume  $[\text{NonContingent } (p^-) \text{ in } v]$ 
  hence  $[\Box(\neg(p^-)) \vee \Box(p^-) \text{ in } v]$ 
    unfolding NonContingent-def Necessary-defs Impossible-defs
    by (rule oth-class-taut-3-e[equiv-lr])
  hence  $[\Box(p) \vee \Box(p^-) \text{ in } v]$ 
    apply cut-tac

```

```

    apply (PLM-subst-goal-method  $\lambda\varphi . \Box\varphi \vee \Box(p^-) \neg(p^-)$ )
    using thm-relation-negation-4 by auto
  hence  $\Box(p) \vee \Box(\neg p)$  in v
    apply cut-tac
    apply (PLM-subst-method  $p^- \neg p$ )
    using thm-relation-negation-3 by auto
  thus  $[NonContingent\ p\ in\ v]$ 
  unfolding NonContingent-def Necessary-defs Impossible-defs .
qed

```

```

lemma thm-cont-propos-2[PLM]:
   $[Contingent\ p \equiv \Diamond p \ \& \ \Diamond(\neg p)\ in\ v]$ 
proof (rule  $\equiv I$ ; rule CP)
  assume  $[Contingent\ p\ in\ v]$ 
  hence  $\neg(\Box p \vee \Box(\neg p))$  in v
    unfolding Contingent-def Necessary-defs Impossible-defs .
  hence  $[(\neg\Box p) \ \& \ (\neg\Box(\neg p))\ in\ v]$ 
    by (rule oth-class-taut-6-d[equiv-lr])
  hence  $[(\Diamond\neg(\neg p)) \ \& \ (\Diamond\neg p)\ in\ v]$ 
    using KBasic2-2[equiv-lr] &I &E by meson
  thus  $[(\Diamond p) \ \& \ (\Diamond(\neg p))\ in\ v]$ 
    apply cut-tac apply PLM-solver
    apply (PLM-subst-method  $\neg\neg p\ p$ )
    using oth-class-taut-4-b[equiv-sym] by auto
next
  assume  $[(\Diamond p) \ \& \ (\Diamond\neg(p))\ in\ v]$ 
  hence  $[(\Diamond\neg(\neg p)) \ \& \ (\Diamond\neg(p))\ in\ v]$ 
    apply cut-tac apply PLM-solver
    apply (PLM-subst-method  $p\ \neg\neg p$ )
    using oth-class-taut-4-b by auto
  hence  $[(\neg\Box p) \ \& \ (\neg\Box(\neg p))\ in\ v]$ 
    using KBasic2-2[equiv-rl] &I &E by meson
  hence  $\neg(\Box(p) \vee \Box(\neg p))$  in v
    by (rule oth-class-taut-6-d[equiv-rl])
  thus  $[Contingent\ p\ in\ v]$ 
    unfolding Contingent-def Necessary-defs Impossible-defs .
qed

```

```

lemma thm-cont-propos-3[PLM]:
   $[Contingent\ (p::o) \equiv Contingent\ (p^-)\ in\ v]$ 
  using thm-cont-propos-1
  unfolding NonContingent-def Contingent-def
  by (rule oth-class-taut-5-d[equiv-lr])

```

context

begin

```

private definition p0 where
   $p_0 \equiv \forall x. (\Box E!, x^P) \rightarrow (\Box E!, x^P)$ 

```

```

lemma thm-noncont-propos-1[PLM]:
   $[Necessary\ p_0\ in\ v]$ 
  unfolding Necessary-defs p0-def
  apply (rule RN, rule  $\forall I$ )
  using if-p-then-p .

```

```

lemma thm-noncont-propos-2[PLM]:
   $[Impossible\ (p_0^-)\ in\ v]$ 
  unfolding Impossible-defs
  apply (PLM-subst-method  $\neg p_0\ p_0^-$ )
    using thm-relation-negation-3[equiv-sym] apply simp
  apply (PLM-subst-method  $p_0\ \neg\neg p_0$ )
    using oth-class-taut-4-b apply simp
  using thm-noncont-propos-1 unfolding Necessary-defs

```

```

by simp

lemma thm-noncont-propos-3[PLM]:
  [NonContingent (p0) in v]
  unfolding NonContingent-def using thm-noncont-propos-1
  by (rule  $\vee I(1)$ )

lemma thm-noncont-propos-4[PLM]:
  [NonContingent (p0-) in v]
  unfolding NonContingent-def using thm-noncont-propos-2
  by (rule  $\vee I(2)$ )

lemma thm-noncont-propos-5[PLM]:
  [ $\exists (p::o) q . p \neq q \ \& \ \text{NonContingent } p \ \& \ \text{NonContingent } q$  in v]
  apply (rule-tac  $\alpha=p_0$  in  $\exists I$ , rule-tac  $\alpha=p_0^-$  in  $\exists I$ )
  using  $\exists I$  thm-relation-negation-6 thm-noncont-propos-3
  thm-noncont-propos-4 &I by simp

private definition q0 where
  q0  $\equiv \exists x . (\!|E!, x^P|\!) \ \& \ \Diamond(\neg(\!|E!, x^P|\!))$ 

lemma basic-prop-1[PLM]:
  [ $\exists p . \Diamond p \ \& \ \Diamond(\neg p)$  in v]
  apply (rule-tac  $\alpha=q_0$  in  $\exists I$ ) unfolding q0-def
  using qml-4[axiom-instance] by simp

lemma basic-prop-2[PLM]:
  [Contingent q0 in v]
  unfolding Contingent-def Necessary-defs Impossible-defs
  apply (rule oth-class-taut-6-d[equiv-rl])
  apply (PLM-subst-goal-method  $\lambda \varphi . (\neg\Box(\varphi)) \ \& \ \neg\Box\neg q_0 \ \neg\neg q_0$ )
  using oth-class-taut-4-b[equiv-sym] apply simp
  using qml-4[axiom-instance, conj-sym]
  unfolding q0-def diamond-def by simp

lemma basic-prop-3[PLM]:
  [Contingent (q0-) in v]
  apply (rule thm-cont-propos-3[equiv-lr])
  using basic-prop-2 .

lemma basic-prop-4[PLM]:
  [ $\exists (p::o) q . p \neq q \ \& \ \text{Contingent } p \ \& \ \text{Contingent } q$  in v]
  apply (rule-tac  $\alpha=q_0$  in  $\exists I$ , rule-tac  $\alpha=q_0^-$  in  $\exists I$ )
  using thm-relation-negation-6 basic-prop-2 basic-prop-3 &I by simp

lemma four-distinct-props-1[PLM]:
  [NonContingent (p:: $\Pi_0$ )  $\rightarrow (\neg(\exists q . \text{Contingent } q \ \& \ q = p))$  in v]
  proof (rule CP)
    assume [NonContingent p in v]
    hence [ $\neg(\text{Contingent } p)$  in v]
    unfolding NonContingent-def Contingent-def
    apply cut-tac by PLM-solver
    moreover {
      assume [ $\exists q . \text{Contingent } q \ \& \ q = p$  in v]
      then obtain r where [Contingent r & r = p in v]
      by (rule  $\exists E$ )
      hence [Contingent p in v]
      using &E l-identity[axiom-instance, deduction, deduction]
      by blast
    }
    ultimately show [ $\neg(\exists q . \text{Contingent } q \ \& \ q = p)$  in v]
    using modus-tollens-1 CP by blast
  qed

```



```

thus  $[(p_0^-) \neq (q_0^-) \text{ in } v]$ 
  using four-distinct-props-2[deduction, OF basic-prop-3]
    modus-tollens-1 CP
  by blast
next
  show  $[q_0 \neq (q_0^-) \text{ in } v]$ 
    by (rule thm-relation-negation-6)
qed

lemma cont-true-cont-1[PLM]:
  [ContingentlyTrue  $p \rightarrow$  Contingent  $p$  in  $v$ ]
  apply (rule CP, rule thm-cont-propos-2[equiv-rl])
  unfolding ContingentlyTrue-def
  apply (rule &I, drule &E(1))
  using T $\Diamond$ [deduction] apply simp
  by (rule &E(2))

lemma cont-true-cont-2[PLM]:
  [ContingentlyFalse  $p \rightarrow$  Contingent  $p$  in  $v$ ]
  apply (rule CP, rule thm-cont-propos-2[equiv-rl])
  unfolding ContingentlyFalse-def
  apply (rule &I, drule &E(2))
  apply simp
  apply (drule &E(1))
  using T $\Diamond$ [deduction] by simp

lemma cont-true-cont-3[PLM]:
  [ContingentlyTrue  $p \equiv$  ContingentlyFalse  $(p^-)$  in  $v$ ]
  unfolding ContingentlyTrue-def ContingentlyFalse-def
  apply (PLM-subst-method  $\neg p p^-$ )
  using thm-relation-negation-3[equiv-sym] apply simp
  apply (PLM-subst-method  $p \neg \neg p$ )
  by PLM-solver +

lemma cont-true-cont-4[PLM]:
  [ContingentlyFalse  $p \equiv$  ContingentlyTrue  $(p^-)$  in  $v$ ]
  unfolding ContingentlyTrue-def ContingentlyFalse-def
  apply (PLM-subst-method  $\neg p p^-$ )
  using thm-relation-negation-3[equiv-sym] apply simp
  apply (PLM-subst-method  $p \neg \neg p$ )
  by PLM-solver +

lemma cont-tf-thm-1[PLM]:
  [ContingentlyTrue  $q_0 \vee$  ContingentlyFalse  $q_0$  in  $v$ ]
  proof –
    have  $[q_0 \vee \neg q_0 \text{ in } v]$ 
      by PLM-solver
    moreover {
      assume  $[q_0 \text{ in } v]$ 
      hence  $[q_0 \ \& \ \Diamond \neg q_0 \text{ in } v]$ 
        unfolding q0-def
        using qml-4[axiom-instance, conj2] &I
        by auto
    }
    moreover {
      assume  $[\neg q_0 \text{ in } v]$ 
      hence  $[(\neg q_0) \ \& \ \Diamond q_0 \text{ in } v]$ 
        unfolding q0-def
        using qml-4[axiom-instance, conj1] &I
        by auto
    }
  ultimately show ?thesis
    unfolding ContingentlyTrue-def ContingentlyFalse-def

```



```

    using  $\vee E(4)$  CP by auto
qed

lemma cont-tf-thm-2[PLM]:
  [ContingentlyFalse  $q_0 \vee$  ContingentlyFalse  $(q_0^-)$  in  $v$ ]
  using cont-tf-thm-1 cont-true-cont-3[where  $p=q_0$ ]
    cont-true-cont-4[where  $p=q_0$ ]
  apply cut-tac by PLM-solver

lemma cont-tf-thm-3[PLM]:
  [ $\exists p .$  ContingentlyTrue  $p$  in  $v$ ]
  proof (rule  $\vee E(1)$ ; (rule CP)?)
    show [ContingentlyTrue  $q_0 \vee$  ContingentlyFalse  $q_0$  in  $v$ ]
      using cont-tf-thm-1 .
  next
    assume [ContingentlyTrue  $q_0$  in  $v$ ]
    thus ?thesis
      using  $\exists I$  by metis
  next
    assume [ContingentlyFalse  $q_0$  in  $v$ ]
    hence [ContingentlyTrue  $(q_0^-)$  in  $v$ ]
      using cont-true-cont-4[equiv-lr] by simp
    thus ?thesis
      using  $\exists I$  by metis
  qed

lemma cont-tf-thm-4[PLM]:
  [ $\exists p .$  ContingentlyFalse  $p$  in  $v$ ]
  proof (rule  $\vee E(1)$ ; (rule CP)?)
    show [ContingentlyTrue  $q_0 \vee$  ContingentlyFalse  $q_0$  in  $v$ ]
      using cont-tf-thm-1 .
  next
    assume [ContingentlyTrue  $q_0$  in  $v$ ]
    hence [ContingentlyFalse  $(q_0^-)$  in  $v$ ]
      using cont-true-cont-3[equiv-lr] by simp
    thus ?thesis
      using  $\exists I$  by metis
  next
    assume [ContingentlyFalse  $q_0$  in  $v$ ]
    thus ?thesis
      using  $\exists I$  by metis
  qed

lemma cont-tf-thm-5[PLM]:
  [ContingentlyTrue  $p \ \& \$  Necessary  $q \rightarrow p \neq q$  in  $v$ ]
  proof (rule CP)
    assume [ContingentlyTrue  $p \ \& \$  Necessary  $q$  in  $v$ ]
    hence 1: [ $\Diamond(\neg p) \ \& \ \Box q$  in  $v$ ]
      unfolding ContingentlyTrue-def Necessary-defs
      using  $\&E \ \&I$  by blast
    hence [ $\neg \Box p$  in  $v$ ]
      apply cut-tac apply (drule  $\&E(1)$ )
      unfolding diamond-def
      apply (PLM-subst-method  $\neg \neg p \ p$ )
      using oth-class-taut-4-b[equiv-sym] by auto
    moreover {
      assume [ $p = q$  in  $v$ ]
      hence [ $\Box p$  in  $v$ ]
        using l-identity[where  $\alpha=q$  and  $\beta=p$  and  $\varphi=\lambda x . \Box x$ ,
          axiom-instance, deduction, deduction]
          1[conj2] id-eq-prop-prop-8-b[deduction]
        by blast
    }
  }

```

```

ultimately show  $[p \neq q \text{ in } v]$ 
  using modus-tollens-1 CP by blast
qed

lemma cont-tf-thm-6[PLM]:
   $[(\text{ContingentlyFalse } p \ \& \ \text{Impossible } q) \rightarrow p \neq q \text{ in } v]$ 
proof (rule CP)
  assume  $[\text{ContingentlyFalse } p \ \& \ \text{Impossible } q \text{ in } v]$ 
  hence 1:  $[\Diamond p \ \& \ \Box(\neg q) \text{ in } v]$ 
    unfolding ContingentlyFalse-def Impossible-defs
    using &E &I by blast
  hence  $[\neg \Diamond q \text{ in } v]$ 
    unfolding diamond-def apply cut-tac by PLM-solver
  moreover {
    assume  $[p = q \text{ in } v]$ 
    hence  $[\Diamond q \text{ in } v]$ 
      using l-identity[axiom-instance, deduction, deduction] 1[conj1]
      id-eq-prop-prop-8-b[deduction]
      by blast
  }
  ultimately show  $[p \neq q \text{ in } v]$ 
    using modus-tollens-1 CP by blast
qed
end

lemma oa-contingent-1[PLM]:
   $[O! \neq A! \text{ in } v]$ 
proof -
  {
    assume  $[O! = A! \text{ in } v]$ 
    hence  $[(\lambda x. \Diamond(E!, x^P)) = (\lambda x. \neg \Diamond(E!, x^P)) \text{ in } v]$ 
      unfolding Ordinary-def Abstract-def .
    moreover have  $[(\Diamond(\lambda x. \Diamond(E!, x^P)), x^P) \equiv \Diamond(E!, x^P) \text{ in } v]$ 
      apply (rule beta-C-meta-1) by (rule IsPropositional-intros)+
    ultimately have  $[(\Diamond(\lambda x. \neg \Diamond(E!, x^P)), x^P) \equiv \Diamond(E!, x^P) \text{ in } v]$ 
      using l-identity[axiom-instance, deduction, deduction] by fast
    moreover have  $[(\Diamond(\lambda x. \neg \Diamond(E!, x^P)), x^P) \equiv \neg \Diamond(E!, x^P) \text{ in } v]$ 
      apply (rule beta-C-meta-1) by (rule IsPropositional-intros)+
    ultimately have  $[\Diamond(E!, x^P) \equiv \neg \Diamond(E!, x^P) \text{ in } v]$ 
      apply cut-tac by PLM-solver
  }
  thus ?thesis
    using oth-class-taut-1-b modus-tollens-1 CP
    by blast
qed

lemma oa-contingent-2[PLM]:
   $[(\Diamond O!, x^P) \equiv \neg \Diamond A!, x^P \text{ in } v]$ 
proof -
  have  $[(\Diamond(\lambda x. \neg \Diamond(E!, x^P)), x^P) \equiv \neg \Diamond(E!, x^P) \text{ in } v]$ 
    apply (rule beta-C-meta-1)
    by (rule IsPropositional-intros)+
  hence  $[(\neg \Diamond(\lambda x. \neg \Diamond(E!, x^P)), x^P) \equiv \Diamond(E!, x^P) \text{ in } v]$ 
    using oth-class-taut-5-d[equiv-lr] oth-class-taut-4-b[equiv-sym]
     $\equiv E(5)$  by blast
  moreover have  $[(\Diamond(\lambda x. \Diamond(E!, x^P)), x^P) \equiv \Diamond(E!, x^P) \text{ in } v]$ 
    apply (rule beta-C-meta-1)
    by (rule IsPropositional-intros)+
  ultimately show ?thesis
    unfolding Ordinary-def Abstract-def
    apply cut-tac by PLM-solver
qed

```

```

lemma oa-contingent-3[PLM]:
  [( $\langle A!, x^P \rangle \equiv \neg \langle O!, x^P \rangle$ ) in v]
  using oa-contingent-2
  apply cut-tac by PLM-solver

lemma oa-contingent-4[PLM]:
  [Contingent O! in v]
  apply (rule thm-cont-prop-2[equiv-rl], rule &I)
  subgoal
    unfolding Ordinary-def
    apply (PLM-subst1-method  $\lambda x . \Diamond \langle E!, x^P \rangle \lambda x . \langle \lambda x . \Diamond \langle E!, x^P \rangle, x^P \rangle$ )
    apply (rule beta-C-meta-1[equiv-sym]; (rule IsPropositional-intros)+)
    using BF $\Diamond$ [deduction, OF thm-cont-prop-2[equiv-lr, OF thm-cont-e-2, conj1]]
    by (rule T $\Diamond$ [deduction])
  subgoal
    apply (PLM-subst1-method  $\lambda x . \langle A!, x^P \rangle \lambda x . \neg \langle O!, x^P \rangle$ )
    using oa-contingent-3 apply simp
    using cqt-further-5[deduction, conj1, OF A-objects[axiom-instance]]
    by (rule T $\Diamond$ [deduction])
  done

lemma oa-contingent-5[PLM]:
  [Contingent A! in v]
  apply (rule thm-cont-prop-2[equiv-rl], rule &I)
  subgoal
    using cqt-further-5[deduction, conj1, OF A-objects[axiom-instance]]
    by (rule T $\Diamond$ [deduction])
  subgoal
    unfolding Abstract-def
    apply (PLM-subst1-method  $\lambda x . \neg \Diamond \langle E!, x^P \rangle \lambda x . \langle \lambda x . \neg \Diamond \langle E!, x^P \rangle, x^P \rangle$ )
    apply (rule beta-C-meta-1[equiv-sym]; (rule IsPropositional-intros)+)
    apply (PLM-subst1-method  $\lambda x . \Diamond \langle E!, x^P \rangle \lambda x . \neg \neg \Diamond \langle E!, x^P \rangle$ )
    using oth-class-taut-4-b apply simp
    using BF $\Diamond$ [deduction, OF thm-cont-prop-2[equiv-lr, OF thm-cont-e-2, conj1]]
    by (rule T $\Diamond$ [deduction])
  done

lemma oa-contingent-6[PLM]:
  [( $O!^- \neq A!^-$ ) in v]
  proof –
  {
    assume [( $O!^- = A!^-$ ) in v]
    hence [( $\lambda x . \neg \langle O!, x^P \rangle = \lambda x . \neg \langle A!, x^P \rangle$ ) in v]
    unfolding propnot-defs .
    moreover have [( $\langle \lambda x . \neg \langle O!, x^P \rangle, x^P \rangle \equiv \neg \langle O!, x^P \rangle$ ) in v]
    apply (rule beta-C-meta-1)
    by (rule IsPropositional-intros)+
    ultimately have [( $\langle \lambda x . \neg \langle A!, x^P \rangle, x^P \rangle \equiv \neg \langle O!, x^P \rangle$ ) in v]
    using l-identity[axiom-instance, deduction, deduction]
    by fast
    hence [( $\neg \langle A!, x^P \rangle \equiv \neg \langle O!, x^P \rangle$ ) in v]
    apply cut-tac
    apply (PLM-subst-method ( $\langle \lambda x . \neg \langle A!, x^P \rangle, x^P \rangle (\neg \langle A!, x^P \rangle)$ )
    apply (rule beta-C-meta-1; (rule IsPropositional-intros)+)
    by assumption
    hence [( $\langle O!, x^P \rangle \equiv \neg \langle O!, x^P \rangle$ ) in v]
    using oa-contingent-2 apply cut-tac by PLM-solver
  }
  thus ?thesis
  using oth-class-taut-1-b modus-tollens-1 CP
  by blast
qed

```

```

lemma oa-contingent-7[PLM]:
  [( $O!^-, x^P$ )  $\equiv$   $\neg$ ( $A!^-, x^P$ ) in v]
proof -
  have [( $\neg$ ( $\lambda x. \neg$ ( $A!, x^P$ ),  $x^P$ ))  $\equiv$  ( $A!, x^P$ ) in v]
    apply (PLM-subst-method ( $\neg$ ( $A!, x^P$ )) ( $\lambda x. \neg$ ( $A!, x^P$ ),  $x^P$ ))
    apply (rule beta-C-meta-1[equiv-sym];
      (rule IsPropositional-intros)+)
    using oth-class-taut-4-b[equiv-sym] by auto
  moreover have [( $\lambda x. \neg$ ( $O!, x^P$ ),  $x^P$ )  $\equiv$   $\neg$ ( $O!, x^P$ ) in v]
    apply (rule beta-C-meta-1)
    by (rule IsPropositional-intros)+
  ultimately show ?thesis
    unfolding propnot-defs
    using oa-contingent-3
    apply cut-tac by PLM-solver
qed

lemma oa-contingent-8[PLM]:
  [Contingent ( $O!^-$ ) in v]
using oa-contingent-4 thm-cont-prop-3[equiv-lr] by auto

lemma oa-contingent-9[PLM]:
  [Contingent ( $A!^-$ ) in v]
using oa-contingent-5 thm-cont-prop-3[equiv-lr] by auto

lemma oa-facts-1[PLM]:
  [( $O!, x^P$ )  $\rightarrow$   $\Box$ ( $O!, x^P$ ) in v]
proof (rule CP)
  assume [( $O!, x^P$ ) in v]
  hence [ $\Diamond$ ( $E!, x^P$ ) in v]
    unfolding Ordinary-def apply cut-tac
    apply (rule beta-C-meta-1[equiv-lr])
    by (rule IsPropositional-intros | assumption)+
  hence [ $\Box\Diamond$ ( $E!, x^P$ ) in v]
    using qml-3[axiom-instance, deduction] by auto
  thus [ $\Box$ ( $O!, x^P$ ) in v]
    unfolding Ordinary-def
    apply cut-tac
    apply (PLM-subst-method  $\Diamond$ ( $E!, x^P$ ) ( $\lambda x. \Diamond$ ( $E!, x^P$ ),  $x^P$ ))
    by (rule beta-C-meta-1[equiv-sym],
      (rule IsPropositional-intros | assumption)+)
qed

lemma oa-facts-2[PLM]:
  [( $A!, x^P$ )  $\rightarrow$   $\Box$ ( $A!, x^P$ ) in v]
proof (rule CP)
  assume [( $A!, x^P$ ) in v]
  hence [ $\neg\Diamond$ ( $E!, x^P$ ) in v]
    unfolding Abstract-def apply cut-tac
    apply (rule beta-C-meta-1[equiv-lr])
    by (rule IsPropositional-intros | assumption)+
  hence [ $\Box\Box\neg$ ( $E!, x^P$ ) in v]
    using KBasic2-4[equiv-rl] 4 $\Box$ [deduction] by auto
  hence [ $\Box\neg\Diamond$ ( $E!, x^P$ ) in v]
    apply cut-tac
    apply (PLM-subst-method  $\Box\neg$ ( $E!, x^P$ )  $\neg\Diamond$ ( $E!, x^P$ ))
    using KBasic2-4 by auto
  thus [ $\Box$ ( $A!, x^P$ ) in v]
    unfolding Abstract-def
    apply cut-tac
    apply (PLM-subst-method  $\neg\Diamond$ ( $E!, x^P$ ) ( $\lambda x. \neg\Diamond$ ( $E!, x^P$ ),  $x^P$ ))
    by (rule beta-C-meta-1[equiv-sym], (rule IsPropositional-intros | assumption)+)
qed

```

```

lemma oa-facts-3[PLM]:
  [ $\Diamond \langle O!, x^P \rangle \rightarrow \langle O!, x^P \rangle$  in v]
  using oa-facts-1 by (rule derived-S5-rules-2-b)

lemma oa-facts-4[PLM]:
  [ $\Diamond \langle A!, x^P \rangle \rightarrow \langle A!, x^P \rangle$  in v]
  using oa-facts-2 by (rule derived-S5-rules-2-b)

lemma oa-facts-5[PLM]:
  [ $\Diamond \langle O!, x^P \rangle \equiv \Box \langle O!, x^P \rangle$  in v]
  using oa-facts-1[deduction, OF oa-facts-3[deduction]]
    T $\Diamond$ [deduction, OF qml-2[axiom-instance, deduction]]
     $\equiv I$  CP by blast

lemma oa-facts-6[PLM]:
  [ $\Diamond \langle A!, x^P \rangle \equiv \Box \langle A!, x^P \rangle$  in v]
  using oa-facts-2[deduction, OF oa-facts-4[deduction]]
    T $\Diamond$ [deduction, OF qml-2[axiom-instance, deduction]]
     $\equiv I$  CP by blast

lemma oa-facts-7[PLM]:
  [ $\langle O!, x^P \rangle \equiv \mathcal{A} \langle O!, x^P \rangle$  in v]
  apply (rule  $\equiv I$ ; rule CP)
  apply (rule nec-imp-act[deduction, OF oa-facts-1[deduction]]; assumption)
proof –
  assume [ $\mathcal{A} \langle O!, x^P \rangle$  in v]
  hence [ $\mathcal{A} \langle \Diamond \langle E!, x^P \rangle \rangle$  in v]
    unfolding Ordinary-def apply cut-tac
    apply (PLM-subst-method ( $\langle \lambda x. \Diamond \langle E!, x^P \rangle, x^P \rangle \Diamond \langle E!, x^P \rangle$ )
      by (rule beta-C-meta-1, (rule IsPropositional-intros | assumption))+)
    hence [ $\Diamond \langle E!, x^P \rangle$  in v]
      using Act-Basic-6[equiv-rl] by auto
    thus [ $\langle O!, x^P \rangle$  in v]
      unfolding Ordinary-def apply cut-tac
      apply (PLM-subst-method ( $\Diamond \langle E!, x^P \rangle \langle \lambda x. \Diamond \langle E!, x^P \rangle, x^P \rangle$ )
        by (rule beta-C-meta-1[equiv-sym],
          (rule IsPropositional-intros | assumption))+)
qed

lemma oa-facts-8[PLM]:
  [ $\langle A!, x^P \rangle \equiv \mathcal{A} \langle A!, x^P \rangle$  in v]
  apply (rule  $\equiv I$ ; rule CP)
  apply (rule nec-imp-act[deduction, OF oa-facts-2[deduction]]; assumption)
proof –
  assume [ $\mathcal{A} \langle A!, x^P \rangle$  in v]
  hence [ $\mathcal{A} \langle \neg \Diamond \langle E!, x^P \rangle \rangle$  in v]
    unfolding Abstract-def apply cut-tac
    apply (PLM-subst-method ( $\langle \lambda x. \neg \Diamond \langle E!, x^P \rangle, x^P \rangle \neg \Diamond \langle E!, x^P \rangle$ )
      by (rule beta-C-meta-1, (rule IsPropositional-intros | assumption))+)
    hence [ $\mathcal{A} \langle \Box \neg \langle E!, x^P \rangle \rangle$  in v]
      apply cut-tac
      apply (PLM-subst-method ( $\neg \Diamond \langle E!, x^P \rangle \langle \Box \neg \langle E!, x^P \rangle \rangle$ )
        using KBasic2-4[equiv-sym] by auto
      hence [ $\neg \Diamond \langle E!, x^P \rangle$  in v]
        using qml-act-2[axiom-instance, equiv-rl] KBasic2-4[equiv-lr] by auto
      thus [ $\langle A!, x^P \rangle$  in v]
        unfolding Abstract-def apply cut-tac
        apply (PLM-subst-method ( $\neg \Diamond \langle E!, x^P \rangle \langle \lambda x. \neg \Diamond \langle E!, x^P \rangle, x^P \rangle$ )
          by (rule beta-C-meta-1[equiv-sym], (rule IsPropositional-intros | assumption))+)
qed

lemma cont-nec-fact1-1[PLM]:

```

```

[WeaklyContingent  $F \equiv \text{WeaklyContingent } (F^-)$  in  $v$ ]
proof (rule  $\equiv I$ ; rule  $CP$ )
  assume [WeaklyContingent  $F$  in  $v$ ]
  hence  $wc\text{-}def$ : [Contingent  $F \ \& \ (\forall x . (\Diamond(F, x^P) \rightarrow \Box(F, x^P)))$  in  $v$ ]
    unfolding WeaklyContingent-def .
  have [Contingent  $(F^-)$  in  $v$ ]
    using  $wc\text{-}def[conj1]$  by (rule  $thm\text{-}cont\text{-}prop\text{-}3[equiv\text{-}lr]$ )
  moreover {
    {
      fix  $x$ 
      assume [ $\Diamond(F^-, x^P)$  in  $v$ ]
      hence [ $\neg\Box(F, x^P)$  in  $v$ ]
        unfolding diamond-def apply cut-tac
        apply (PLM-subst-method  $\neg(F^-, x^P)$   $(F, x^P)$ )
        using  $thm\text{-}relation\text{-}negation\text{-}2\text{-}1$  by auto
      moreover {
        assume [ $\neg\Box(F^-, x^P)$  in  $v$ ]
        hence [ $\neg\Box(\lambda x. \neg(F, x^P), x^P)$  in  $v$ ]
          unfolding propnot-defs .
        hence [ $\Diamond(F, x^P)$  in  $v$ ]
          unfolding diamond-def
          apply cut-tac apply (PLM-subst-method  $(\lambda x. \neg(F, x^P), x^P)$   $\neg(F, x^P)$ )
          apply (rule  $\beta\text{-}C\text{-}meta\text{-}1$ ; rule  $IsPropositional\text{-}intros$ )
          by simp
        hence [ $\Box(F, x^P)$  in  $v$ ]
          using  $wc\text{-}def[conj2]$   $cqt\text{-}1[axiom\text{-}instance, deduction]$ 
           $modus\text{-}ponens$  by fast
      }
      ultimately have [ $\Box(F^-, x^P)$  in  $v$ ]
        using  $\neg\neg E$   $modus\text{-}tollens\text{-}1$   $CP$  by blast
    }
    hence [ $\forall x . \Diamond(F^-, x^P) \rightarrow \Box(F^-, x^P)$  in  $v$ ]
      using  $\forall I$   $CP$  by fast
  }
  ultimately show [WeaklyContingent  $(F^-)$  in  $v$ ]
    unfolding WeaklyContingent-def by (rule  $\&I$ )
next
  assume [WeaklyContingent  $(F^-)$  in  $v$ ]
  hence  $wc\text{-}def$ : [Contingent  $(F^-) \ \& \ (\forall x . (\Diamond(F^-, x^P) \rightarrow \Box(F^-, x^P)))$  in  $v$ ]
    unfolding WeaklyContingent-def .
  have [Contingent  $F$  in  $v$ ]
    using  $wc\text{-}def[conj1]$  by (rule  $thm\text{-}cont\text{-}prop\text{-}3[equiv\text{-}rl]$ )
  moreover {
    {
      fix  $x$ 
      assume [ $\Diamond(F, x^P)$  in  $v$ ]
      hence [ $\neg\Box(F^-, x^P)$  in  $v$ ]
        unfolding diamond-def apply cut-tac
        apply (PLM-subst-method  $\neg(F, x^P)$   $(F^-, x^P)$ )
        using  $thm\text{-}relation\text{-}negation\text{-}1\text{-}1[equiv\text{-}sym]$  by auto
      moreover {
        assume [ $\neg\Box(F, x^P)$  in  $v$ ]
        hence [ $\Diamond(F^-, x^P)$  in  $v$ ]
          unfolding diamond-def
          apply cut-tac apply (PLM-subst-method  $(F, x^P)$   $\neg(F^-, x^P)$ )
          using  $thm\text{-}relation\text{-}negation\text{-}2\text{-}1[equiv\text{-}sym]$  by auto
        hence [ $\Box(F^-, x^P)$  in  $v$ ]
          using  $wc\text{-}def[conj2]$   $cqt\text{-}1[axiom\text{-}instance, deduction]$ 
           $modus\text{-}ponens$  by fast
      }
      ultimately have [ $\Box(F, x^P)$  in  $v$ ]
        using  $\neg\neg E$   $modus\text{-}tollens\text{-}1$   $CP$  by blast
    }
  }

```

hence $[\forall x . \Diamond(\Box(F, x^P)) \rightarrow \Box(\Box(F, x^P)) \text{ in } v]$
 using $\forall I$ CP by fast
 }
 ultimately show $[WeaklyContingent(F) \text{ in } v]$
 unfolding *WeaklyContingent-def* by (rule $\&I$)
 qed

lemma *cont-nec-fact1-2[PLM]*:
 $[(WeaklyContingent F \ \& \ \neg(WeaklyContingent G)) \rightarrow (F \neq G) \text{ in } v]$
 using *l-identity[axiom-instance, deduction]* $\&E$ $\&I$
modus-tollens-1 CP by metis

lemma *cont-nec-fact2-1[PLM]*:
 $[WeaklyContingent(O!) \text{ in } v]$
 unfolding *WeaklyContingent-def*
 apply (rule $\&I$)
 using *oa-contingent-4* apply simp
 using *oa-facts-5* unfolding *equiv-def*
 using $\&E(1) \forall I$ by fast

lemma *cont-nec-fact2-2[PLM]*:
 $[WeaklyContingent(A!) \text{ in } v]$
 unfolding *WeaklyContingent-def*
 apply (rule $\&I$)
 using *oa-contingent-5* apply simp
 using *oa-facts-6* unfolding *equiv-def*
 using $\&E(1) \forall I$ by fast

lemma *cont-nec-fact2-3[PLM]*:
 $[\neg(WeaklyContingent(E!)) \text{ in } v]$
proof (rule *modus-tollens-1, rule CP*)
 assume $[WeaklyContingent E! \text{ in } v]$
 thus $[\forall x . \Diamond(\Box(E!, x^P)) \rightarrow \Box(\Box(E!, x^P)) \text{ in } v]$
 unfolding *WeaklyContingent-def* using $\&E(2)$ by fast
 next
 {
 assume 1: $[\forall x . \Diamond(\Box(E!, x^P)) \rightarrow \Box(\Box(E!, x^P)) \text{ in } v]$
 have $[\exists x . \Diamond(\Box(E!, x^P) \ \& \ \Diamond(\neg(\Box(E!, x^P)))) \text{ in } v]$
 using *qml-4[axiom-instance, conj1, THEN BFs-3[deduction]]* .
 then obtain x where $[\Diamond(\Box(E!, x^P) \ \& \ \Diamond(\neg(\Box(E!, x^P)))) \text{ in } v]$
 by (rule $\exists E$)
 hence $[\Diamond(\Box(E!, x^P) \ \& \ \Diamond(\neg(\Box(E!, x^P)))) \text{ in } v]$
 using *KBasic2-8[deduction]* *S5Basic-8[deduction]*
 $\&I$ $\&E$ by blast
 hence $[\Box(\Box(E!, x^P) \ \& \ (\neg\Box(E!, x^P))) \text{ in } v]$
 using 1[*THEN $\forall E$, deduction*] $\&E$ $\&I$
KBasic2-2[equiv-rl] by blast
 hence $[\neg(\forall x . \Diamond(\Box(E!, x^P)) \rightarrow \Box(\Box(E!, x^P))) \text{ in } v]$
 using *oth-class-taut-1-a modus-tollens-1 CP* by blast
 }
 thus $[\neg(\forall x . \Diamond(\Box(E!, x^P)) \rightarrow \Box(\Box(E!, x^P))) \text{ in } v]$
 using *reductio-aa-2 if-p-then-p CP* by meson
 qed

lemma *cont-nec-fact2-4[PLM]*:
 $[\neg(WeaklyContingent(PLM.L)) \text{ in } v]$
proof –
 {
 assume $[WeaklyContingent PLM.L \text{ in } v]$
 hence $[Contingent PLM.L \text{ in } v]$
 unfolding *WeaklyContingent-def* using $\&E(1)$ by blast
 }
 thus ?thesis

```

    using thm-noncont-e-e-3
    unfolding Contingent-def NonContingent-def
    using modus-tollens-2 CP by blast
qed

lemma cont-nec-fact2-5[PLM]:
  [O! ≠ E! & O! ≠ (E!⁻) & O! ≠ PLM.L & O! ≠ (PLM.L⁻) in v]
proof ((rule &I)+)
  show [O! ≠ E! in v]
    using cont-nec-fact2-1 cont-nec-fact2-3
      cont-nec-fact1-2[deduction] &I by simp
next
  have [¬(WeaklyContingent (E!⁻)) in v]
    using cont-nec-fact1-1[THEN oth-class-taut-5-d[equiv-lr], equiv-lr]
      cont-nec-fact2-3 by auto
  thus [O! ≠ (E!⁻) in v]
    using cont-nec-fact2-1 cont-nec-fact1-2[deduction] &I by simp
next
  show [O! ≠ PLM.L in v]
    using cont-nec-fact2-1 cont-nec-fact2-4
      cont-nec-fact1-2[deduction] &I by simp
next
  have [¬(WeaklyContingent (PLM.L⁻)) in v]
    using cont-nec-fact1-1[THEN oth-class-taut-5-d[equiv-lr], equiv-lr]
      cont-nec-fact2-4 by auto
  thus [O! ≠ (PLM.L⁻) in v]
    using cont-nec-fact2-1 cont-nec-fact1-2[deduction] &I by simp
qed

lemma cont-nec-fact2-6[PLM]:
  [A! ≠ E! & A! ≠ (E!⁻) & A! ≠ PLM.L & A! ≠ (PLM.L⁻) in v]
proof ((rule &I)+)
  show [A! ≠ E! in v]
    using cont-nec-fact2-2 cont-nec-fact2-3
      cont-nec-fact1-2[deduction] &I by simp
next
  have [¬(WeaklyContingent (E!⁻)) in v]
    using cont-nec-fact1-1[THEN oth-class-taut-5-d[equiv-lr], equiv-lr]
      cont-nec-fact2-3 by auto
  thus [A! ≠ (E!⁻) in v]
    using cont-nec-fact2-2 cont-nec-fact1-2[deduction] &I by simp
next
  show [A! ≠ PLM.L in v]
    using cont-nec-fact2-2 cont-nec-fact2-4
      cont-nec-fact1-2[deduction] &I by simp
next
  have [¬(WeaklyContingent (PLM.L⁻)) in v]
    using cont-nec-fact1-1[THEN oth-class-taut-5-d[equiv-lr],
      equiv-lr] cont-nec-fact2-4 by auto
  thus [A! ≠ (PLM.L⁻) in v]
    using cont-nec-fact2-2 cont-nec-fact1-2[deduction] &I by simp
qed

lemma id-nec3-1[PLM]:
  [(xP) =E (yP) ≡ (□((xP) =E (yP))) in v]
proof (rule ≡I; rule CP)
  assume [(xP) =E (yP) in v]
  hence [⟦O!, xP⟧ in v] ∧ [⟦O!, yP⟧ in v] ∧ [□(∀ F . ⟦F, xP⟧ ≡ ⟦F, yP⟧) in v]
    using eq-E-simple-1[equiv-lr] using &E by blast
  hence [□(⟦O!, xP⟧ in v) ∧ □(⟦O!, yP⟧ in v)
    ∧ [□□(∀ F . ⟦F, xP⟧ ≡ ⟦F, yP⟧) in v]
    using oa-facts-1[deduction] S5Basic-6[deduction] by blast
  hence [□(⟦O!, xP⟧ & ⟦O!, yP⟧) & □(∀ F . ⟦F, xP⟧ ≡ ⟦F, yP⟧) in v]

```



```

    using &I KBasic-3[equiv-rl] by presburger
  thus  $\Box((x^P) =_E (y^P))$  in v]
  apply cut-tac
  apply (PLM-subst-method
    ( $\Box(O!, x^P) \ \& \ \Box(O!, y^P) \ \& \ \Box(\forall F. \Box(F, x^P) \equiv \Box(F, y^P))$ )
    ( $(x^P) =_E (y^P)$ )
    using eq-E-simple-1[equiv-sym] by auto
  next
  assume  $\Box((x^P) =_E (y^P))$  in v]
  thus  $\Box((x^P) =_E (y^P))$  in v]
  using qml-2[axiom-instance, deduction] by simp
qed

lemma id-nec3-2[PLM]:
 $\Box((x^P) =_E (y^P)) \equiv ((x^P) =_E (y^P))$  in v]
proof (rule  $\equiv I$ ; rule CP)
  assume  $\Box((x^P) =_E (y^P))$  in v]
  thus  $\Box((x^P) =_E (y^P))$  in v]
  using derived-S5-rules-2-b[deduction] id-nec3-1[equiv-lr]
    CP modus-ponens by blast
next
  assume  $\Box((x^P) =_E (y^P))$  in v]
  thus  $\Box((x^P) =_E (y^P))$  in v]
  by (rule TBasic[deduction])
qed

lemma thm-neg-eqE[PLM]:
 $\Box((x^P) \neq_E (y^P)) \equiv \neg((x^P) =_E (y^P))$  in v]
proof -
  have  $\Box((x^P) \neq_E (y^P))$  in v] =  $\Box(\Box(\lambda^2 (\lambda x y. (x^P) =_E (y^P)))^\neg, x^P, y^P)$  in v]
  unfolding not-identical-E-def by simp
  also have ... =  $\Box(\neg(\Box(\lambda^2 (\lambda x y. (x^P) =_E (y^P))))^\neg, x^P, y^P)$  in v]
  unfolding propnot-defs using beta-C-meta-2[equiv-lr]
    beta-C-meta-2[equiv-rl] IsPropositional-intros by fast
  also have ... =  $\Box(\neg((x^P) =_E (y^P)))$  in v]
  apply (PLM-subst-method
    ( $\Box(\lambda^2 (\lambda x y. (x^P) =_E (y^P)))^\neg, x^P, y^P$ )
    ( $(x^P) =_E (y^P)$ )
    apply (rule beta-C-meta-2) unfolding identity-defs
    apply (rule IsPropositional-intros)
    by auto
  finally show ?thesis
    using  $\equiv I$  CP by presburger
qed

lemma id-nec4-1[PLM]:
 $\Box((x^P) \neq_E (y^P)) \equiv \Box(\neg((x^P) =_E (y^P)))$  in v]
proof -
  have  $\Box(\neg((x^P) =_E (y^P))) \equiv \Box(\neg((x^P) =_E (y^P)))$  in v]
  using id-nec3-2[equiv-sym] oth-class-taut-5-d[equiv-lr]
    KBasic2-4[equiv-sym] intro-elim-6-e by fast
  thus ?thesis
    apply cut-tac
    apply (PLM-subst-method  $\neg((x^P) =_E (y^P))$   $(x^P) \neq_E (y^P)$ )
    using thm-neg-eqE[equiv-sym] by auto
qed

lemma id-nec4-2[PLM]:
 $\Box((x^P) \neq_E (y^P)) \equiv ((x^P) \neq_E (y^P))$  in v]
using  $\equiv I$  id-nec4-1[equiv-lr] derived-S5-rules-2-b CP T $\Box$  by simp

lemma id-act-1[PLM]:
 $\Box((x^P) =_E (y^P)) \equiv (\mathcal{A}((x^P) =_E (y^P)))$  in v]

```

```

proof (rule  $\equiv I$ ; rule CP)
  assume  $[(x^P) =_E (y^P)]$  in v
  hence  $[\Box((x^P) =_E (y^P))]$  in v
    using id-nec3-1[equiv-lr] by auto
  thus  $[\mathcal{A}((x^P) =_E (y^P))]$  in v
    using nec-imp-act[deduction] by fast
next
  assume  $[\mathcal{A}((x^P) =_E (y^P))]$  in v
  hence  $[\mathcal{A}(\Box O!, x^P) \ \& \ \Box O!, y^P) \ \& \ \Box(\forall F. \Box(F, x^P) \equiv \Box(F, y^P))]$  in v
    apply cut-tac
    apply (PLM-subst-method
       $(x^P) =_E (y^P)$ 
       $(\Box O!, x^P) \ \& \ \Box O!, y^P) \ \& \ \Box(\forall F. \Box(F, x^P) \equiv \Box(F, y^P))$ )
    using eq-E-simple-1 by auto
  hence  $[\mathcal{A}(\Box O!, x^P) \ \& \ \mathcal{A}(\Box O!, y^P) \ \& \ \mathcal{A}(\Box(\forall F. \Box(F, x^P) \equiv \Box(F, y^P)))]$  in v
    using Act-Basic-2[equiv-lr] &I &E by meson
  thus  $[(x^P) =_E (y^P)]$  in v
    apply cut-tac apply (rule eq-E-simple-1[equiv-rl])
    using oa-facts-7[equiv-rl] qml-act-2[axiom-instance, equiv-rl]
      &I &E by meson
qed

```

```

lemma id-act-2[PLM]:
   $[(x^P) \neq_E (y^P)] \equiv (\mathcal{A}((x^P) \neq_E (y^P)))$  in v
  apply (PLM-subst-method  $(\neg((x^P) =_E (y^P)))$   $((x^P) \neq_E (y^P))$ )
    using thm-neg-eqE[equiv-sym] apply simp
  using id-act-1 oth-class-taut-5-d[equiv-lr] thm-neg-eqE intro-elim-6-e
    logic-actual-nec-1[axiom-instance, equiv-sym] by meson

```

end

```

class id-act = id-eq +
  assumes id-act-prop:  $[\mathcal{A}(\alpha = \beta)]$  in v  $\implies [(\alpha = \beta)]$  in v

```

instantiation $\nu :: id-act$

begin

```

instance proof
  interpret PLM .
  fix x:: $\nu$  and y:: $\nu$  and v::i
  assume  $[\mathcal{A}(x = y)]$  in v
  hence  $[\mathcal{A}(((x^P) =_E (y^P)) \vee (\Box A!, x^P) \ \& \ \Box A!, y^P) \ \& \ \Box(\forall F. \Box(x^P, F) \equiv \Box(y^P, F)))]$  in v
    unfolding identity-defs by auto
  hence  $[\mathcal{A}(((x^P) =_E (y^P)) \vee (\Box A!, x^P) \ \& \ \Box A!, y^P) \ \& \ \Box(\forall F. \Box(x^P, F) \equiv \Box(y^P, F)))]$  in v
    using Act-Basic-10[equiv-lr] by auto
  moreover {
    assume  $[\mathcal{A}(((x^P) =_E (y^P)))]$  in v
    hence  $[(x^P) = (y^P)]$  in v
      using id-act-1[equiv-rl] eq-E-simple-2[deduction] by auto
  }
  moreover {
    assume  $[\mathcal{A}(\Box A!, x^P) \ \& \ \Box A!, y^P) \ \& \ \Box(\forall F. \Box(x^P, F) \equiv \Box(y^P, F))]$  in v
    hence  $[\mathcal{A}(\Box A!, x^P) \ \& \ \mathcal{A}(\Box A!, y^P) \ \& \ \mathcal{A}(\Box(\forall F. \Box(x^P, F) \equiv \Box(y^P, F)))]$  in v
      using Act-Basic-2[equiv-lr] &I &E by meson
    hence  $[\Box A!, x^P) \ \& \ \Box A!, y^P) \ \& \ (\Box(\forall F. \Box(x^P, F) \equiv \Box(y^P, F)))]$  in v
      using oa-facts-8[equiv-rl] qml-act-2[axiom-instance, equiv-rl]
        &I &E by meson
    hence  $[(x^P) = (y^P)]$  in v
      unfolding identity-defs using  $\forall I$  by auto
  }
  ultimately have  $[(x^P) = (y^P)]$  in v
    using intro-elim-4-a CP by meson

```

```

    thus  $[x = y \text{ in } v]$ 
      unfolding identity-defs by auto
    qed
  end

```

```

instantiation  $\Pi_1 :: id-act$ 
begin
  instance proof
    interpret PLM .
    fix  $F :: \Pi_1$  and  $G :: \Pi_1$  and  $v :: i$ 
    show  $[\mathcal{A}(F = G) \text{ in } v] \implies [(F = G) \text{ in } v]$ 
      unfolding identity-defs
      using qml-act-2[axiom-instance,equiv-rl] by auto
    qed
  end

```

```

instantiation  $o :: id-act$ 
begin
  instance proof
    interpret PLM .
    fix  $p :: o$  and  $q :: o$  and  $v :: i$ 
    show  $[\mathcal{A}(p = q) \text{ in } v] \implies [p = q \text{ in } v]$ 
      unfolding identityo-def using id-act-prop by blast
    qed
  end

```

```

instantiation  $\Pi_2 :: id-act$ 
begin
  instance proof
    interpret PLM .
    fix  $F :: \Pi_2$  and  $G :: \Pi_2$  and  $v :: i$ 
    assume  $a: [\mathcal{A}(F = G) \text{ in } v]$ 
    {
      fix  $x$ 
      have  $[\mathcal{A}((\lambda y. \langle F, x^P, y^P \rangle) = (\lambda y. \langle G, x^P, y^P \rangle))$ 
        &  $(\lambda y. \langle F, y^P, x^P \rangle) = (\lambda y. \langle G, y^P, x^P \rangle)) \text{ in } v]$ 
        using a logic-actual-nec-3[axiom-instance, equiv-lr] cqt-basic-4[equiv-lr]  $\forall E$ 
        unfolding identity2-def by blast
      hence  $[((\lambda y. \langle F, x^P, y^P \rangle) = (\lambda y. \langle G, x^P, y^P \rangle))$ 
        &  $((\lambda y. \langle F, y^P, x^P \rangle) = (\lambda y. \langle G, y^P, x^P \rangle)) \text{ in } v]$ 
        using &I &E id-act-prop Act-Basic-2[equiv-lr] by metis
    }
    thus  $[F = G \text{ in } v]$  unfolding identity-defs by (rule  $\forall I$ )
  qed
end

```

```

instantiation  $\Pi_3 :: id-act$ 
begin
  instance proof
    interpret PLM .
    fix  $F :: \Pi_3$  and  $G :: \Pi_3$  and  $v :: i$ 
    assume  $a: [\mathcal{A}(F = G) \text{ in } v]$ 
    let  $?p = \lambda x y. (\lambda z. \langle F, z^P, x^P, y^P \rangle) = (\lambda z. \langle G, z^P, x^P, y^P \rangle)$ 
      &  $(\lambda z. \langle F, x^P, z^P, y^P \rangle) = (\lambda z. \langle G, x^P, z^P, y^P \rangle)$ 
      &  $(\lambda z. \langle F, x^P, y^P, z^P \rangle) = (\lambda z. \langle G, x^P, y^P, z^P \rangle)$ 
    {
      fix  $x$ 
      {
        fix  $y$ 
        have  $[\mathcal{A}(?p \ x \ y) \text{ in } v]$ 
          using a logic-actual-nec-3[axiom-instance, equiv-lr] cqt-basic-4[equiv-lr]  $\forall E$ 
          unfolding identity3-def by blast
        hence  $[?p \ x \ y \text{ in } v]$ 

```

```

      using &I &E id-act-prop Act-Basic-2[equiv-lr] by metis
    }
  hence  $[\forall y . ?p\ x\ y\ in\ v]$ 
    by (rule  $\forall I$ )
}
thus  $[F = G\ in\ v]$ 
  unfolding identity3-def by (rule  $\forall I$ )
qed
end

```

context *PLM*

begin

```

lemma id-act-3[PLM]:
   $[(\alpha::('a::id-act)) = \beta] \equiv \mathcal{A}(\alpha = \beta)\ in\ v$ 
  using  $\equiv I$  CP id-nec[equiv-lr, THEN nec-imp-act[deduction]]
    id-act-prop by metis

```

```

lemma id-act-4[PLM]:
   $[(\alpha::('a::id-act)) \neq \beta] \equiv \mathcal{A}(\alpha \neq \beta)\ in\ v$ 
  using id-act-3[THEN oth-class-taut-5-d[equiv-lr]]
    logic-actual-nec-1[axiom-instance, equiv-sym]
    intro-elim-6-e by blast

```

```

lemma id-act-desc[PLM]:
   $[(y^P) = (\iota x . x = y)\ in\ v]$ 
  using descriptions[axiom-instance, equiv-rl]
    id-act-3[equiv-sym]  $\forall I$  by fast

```

TODO 2. More discussion/thought about eta conversion and the strength of the axiom *lambda-predicates-3** which immediately implies the following very general lemmas.

```

lemma eta-conversion-lemma-1[PLM]:
   $[(\lambda x . \langle F, x^P \rangle) = F\ in\ v]$ 
  using lambda-predicates-3-1[axiom-instance] .

```

```

lemma eta-conversion-lemma-0[PLM]:
   $[(\lambda^0 p) = p\ in\ v]$ 
  using lambda-predicates-3-0[axiom-instance] .

```

```

lemma eta-conversion-lemma-2[PLM]:
   $[(\lambda^2 (\lambda x\ y . \langle F, x^P, y^P \rangle)) = F\ in\ v]$ 
  using lambda-predicates-3-2[axiom-instance] .

```

```

lemma eta-conversion-lemma-3[PLM]:
   $[(\lambda^3 (\lambda x\ y\ z . \langle F, x^P, y^P, z^P \rangle)) = F\ in\ v]$ 
  using lambda-predicates-3-3[axiom-instance] .

```

```

lemma lambda-p-q-p-eq-q[PLM]:
   $[(\lambda^0 p) = (\lambda^0 q)] \equiv (p = q)\ in\ v$ 
  using eta-conversion-lemma-0
    l-identity[axiom-instance, deduction, deduction]
    eta-conversion-lemma-0[eq-sym]  $\equiv I$  CP
  by metis

```

9.12 The Theory of Objects

```

lemma partition-1[PLM]:
   $[\forall x . \langle O!, x^P \rangle \vee \langle A!, x^P \rangle\ in\ v]$ 
  proof (rule  $\forall I$ )
    fix  $x$ 
    have  $[\Diamond \langle E!, x^P \rangle \vee \neg \Diamond \langle E!, x^P \rangle\ in\ v]$ 
      by PLM-solver
    moreover have  $[\Diamond \langle E!, x^P \rangle \equiv \langle \lambda y . \Diamond \langle E!, y^P \rangle, x^P \rangle\ in\ v]$ 
      by (rule beta-C-meta-1[equiv-sym]; (rule IsPropositional-intros)+)

```

moreover have $[(\neg \Diamond \langle E!, x^P \rangle) \equiv \langle \lambda y . \neg \Diamond \langle E!, y^P \rangle, x^P \rangle \text{ in } v]$
by (rule beta-C-meta-1[equiv-sym]; (rule IsPropositional-intros)+)
ultimately show $[\langle O!, x^P \rangle \vee \langle A!, x^P \rangle \text{ in } v]$
unfolding Ordinary-def Abstract-def **by** PLM-solver
qed

lemma partition-2[PLM]:
 $[\neg(\exists x . \langle O!, x^P \rangle \ \& \ \langle A!, x^P \rangle) \text{ in } v]$
proof –
{
 assume $[\exists x . \langle O!, x^P \rangle \ \& \ \langle A!, x^P \rangle \text{ in } v]$
 then obtain b **where** $[\langle O!, b^P \rangle \ \& \ \langle A!, b^P \rangle \text{ in } v]$
 by (rule $\exists E$)
 hence ?thesis
 using &E oa-contingent-2[equiv-lr]
 reductio-aa-2 by fast
}
thus ?thesis
using reductio-aa-2 **by** blast
qed

lemma ord-eq-Eequiv-1[PLM]:
 $[\langle O!, x \rangle \rightarrow (x =_E x) \text{ in } v]$
proof (rule CP)
 assume $[\langle O!, x \rangle \text{ in } v]$
 moreover have $[\Box(\forall F . \langle F, x \rangle \equiv \langle F, x \rangle) \text{ in } v]$
 by PLM-solver
 ultimately show $[(x) =_E (x) \text{ in } v]$
 using &I eq-E-simple-1[equiv-rl] **by** blast
qed

lemma ord-eq-Eequiv-2[PLM]:
 $[(x =_E y) \rightarrow (y =_E x) \text{ in } v]$
proof (rule CP)
 assume $[x =_E y \text{ in } v]$
 hence 1: $[\langle O!, x \rangle \ \& \ \langle O!, y \rangle \ \& \ \Box(\forall F . \langle F, x \rangle \equiv \langle F, y \rangle) \text{ in } v]$
 using eq-E-simple-1[equiv-lr] **by** simp
 have $[\Box(\forall F . \langle F, y \rangle \equiv \langle F, x \rangle) \text{ in } v]$
 apply (PLM-subst1-method
 $\lambda F . \langle F, x \rangle \equiv \langle F, y \rangle$
 $\lambda F . \langle F, y \rangle \equiv \langle F, x \rangle$)
 using oth-class-taut-3-g 1[conj2] **by** auto
 thus $[y =_E x \text{ in } v]$
 using eq-E-simple-1[equiv-rl] 1[conj1]
 &E &I by meson
qed

lemma ord-eq-Eequiv-3[PLM]:
 $[(x =_E y) \ \& \ (y =_E z) \rightarrow (x =_E z) \text{ in } v]$
proof (rule CP)
 assume $a: [(x =_E y) \ \& \ (y =_E z) \text{ in } v]$
 have $[\Box((\forall F . \langle F, x \rangle \equiv \langle F, y \rangle) \ \& \ (\forall F . \langle F, y \rangle \equiv \langle F, z \rangle)) \text{ in } v]$
 using KBasic-3[equiv-rl] a[conj1], THEN eq-E-simple-1[equiv-lr, conj2]
 a[conj2], THEN eq-E-simple-1[equiv-lr, conj2]] **&I by** blast
 moreover {
 {
 fix w
 have $[(\forall F . \langle F, x \rangle \equiv \langle F, y \rangle) \ \& \ (\forall F . \langle F, y \rangle \equiv \langle F, z \rangle)]$
 $\rightarrow (\forall F . \langle F, x \rangle \equiv \langle F, z \rangle) \text{ in } w]$
 by PLM-solver
 }
 hence $[\Box((\forall F . \langle F, x \rangle \equiv \langle F, y \rangle) \ \& \ (\forall F . \langle F, y \rangle \equiv \langle F, z \rangle))$
 $\rightarrow (\forall F . \langle F, x \rangle \equiv \langle F, z \rangle) \text{ in } v]$

```

    by (rule RN)
  }
ultimately have  $[\Box(\forall F . \langle F, x \rangle \equiv \langle F, z \rangle)]$  in  $v$ 
  using qml-1[axiom-instance, deduction, deduction] by blast
thus  $[x =_E z]$  in  $v$ 
  using a[conj1, THEN eq-E-simple-1[equiv-lr, conj1, conj1]]
  using a[conj2, THEN eq-E-simple-1[equiv-lr, conj1, conj2]]
    eq-E-simple-1[equiv-rl] &I
  by presburger
qed

```

```

lemma ord-eq-E-eq[PLM]:
   $[(\langle O!, x^P \rangle \vee \langle O!, y^P \rangle) \rightarrow ((x^P = y^P) \equiv (x^P =_E y^P))]$  in  $v$ 
proof (rule CP)
  assume  $[\langle O!, x^P \rangle \vee \langle O!, y^P \rangle]$  in  $v$ 
  moreover {
    assume  $[\langle O!, x^P \rangle]$  in  $v$ 
    hence  $[(x^P = y^P) \equiv (x^P =_E y^P)]$  in  $v$ 
    using  $\equiv I$  CP l-identity[axiom-instance, deduction, deduction]
      ord-eq-Eequiv-1[deduction] eq-E-simple-2[deduction] by metis
  }
  moreover {
    assume  $[\langle O!, y^P \rangle]$  in  $v$ 
    hence  $[(x^P = y^P) \equiv (x^P =_E y^P)]$  in  $v$ 
    using  $\equiv I$  CP l-identity[axiom-instance, deduction, deduction]
      ord-eq-Eequiv-1[deduction] eq-E-simple-2[deduction] id-eq-2[deduction]
      ord-eq-Eequiv-2[deduction] identity- $\nu$ -def by metis
  }
  ultimately show  $[(x^P = y^P) \equiv (x^P =_E y^P)]$  in  $v$ 
    using intro-elim-4-a CP by blast
qed

```

```

lemma ord-eq-E[PLM]:
   $[(\langle O!, x^P \rangle \& \langle O!, y^P \rangle) \rightarrow ((\forall F . \langle F, x^P \rangle \equiv \langle F, y^P \rangle) \rightarrow x^P =_E y^P)]$  in  $v$ 
proof (rule CP; rule CP)
  assume ord-xy:  $[\langle O!, x^P \rangle \& \langle O!, y^P \rangle]$  in  $v$ 
  assume  $[\forall F . \langle F, x^P \rangle \equiv \langle F, y^P \rangle]$  in  $v$ 
  hence  $[(\lambda z . z^P =_E x^P, x^P) \equiv (\lambda z . z^P =_E x^P, y^P)]$  in  $v$ 
    by (rule  $\forall E$ )
  moreover have  $[(\lambda z . z^P =_E x^P, x^P)]$  in  $v$ 
    apply (rule beta-C-meta-1[equiv-rl])
    unfolding identity_E-infix-def
    apply (rule IsPropositional-intros)+
    using ord-eq-Eequiv-1[deduction] ord-xy[conj1]
    unfolding identity_E-infix-def by simp
  ultimately have  $[(\lambda z . z^P =_E x^P, y^P)]$  in  $v$ 
    using  $\equiv E$  by blast
  hence  $[y^P =_E x^P]$  in  $v$ 
    using beta-C-meta-1[equiv-lr] IsPropositional-intros
    unfolding identity_E-infix-def by fast
  thus  $[x^P =_E y^P]$  in  $v$ 
    by (rule ord-eq-Eequiv-2[deduction])
qed

```

TODO 3. Check the proof in PM. The last part of the proof by contraposition seems invalid.

```

lemma ord-eq-E2[PLM]:
   $[(\langle O!, x^P \rangle \& \langle O!, y^P \rangle) \rightarrow ((x^P \neq y^P) \equiv (\lambda z . z^P =_E x^P) \neq (\lambda z . z^P =_E y^P))]$  in  $v$ 
proof (rule CP; rule  $\equiv I$ ; rule CP)
  assume ord-xy:  $[\langle O!, x^P \rangle \& \langle O!, y^P \rangle]$  in  $v$ 
  assume  $[x^P \neq y^P]$  in  $v$ 
  hence  $[\neg(x^P =_E y^P)]$  in  $v$ 
    using eq-E-simple-2 modus-tollens-1 by fast

```

```

moreover {
  assume  $[(\lambda z . z^P =_E x^P) = (\lambda z . z^P =_E y^P) \text{ in } v]$ 
  moreover have  $[(\lambda z . z^P =_E x^P, x^P) \text{ in } v]$ 
  apply (rule beta-C-meta-1[equiv-rl])
  unfolding identityE-infix-def
  apply (rule IsPropositional-intros)
  using ord-eq-Eequiv-1[deduction] ord-xy[conj1]
  unfolding identityE-infix-def by presburger
  ultimately have  $[(\lambda z . z^P =_E y^P, x^P) \text{ in } v]$ 
  using l-identity[axiom-instance, deduction, deduction] by fast
  hence  $[x^P =_E y^P \text{ in } v]$ 
  using beta-C-meta-1[equiv-lr] IsPropositional-intros
  unfolding identityE-infix-def by fast
}
ultimately show  $[(\lambda z . z^P =_E x^P) \neq (\lambda z . z^P =_E y^P) \text{ in } v]$ 
using modus-tollens-1 CP by blast
next
assume ord-xy:  $[(\lambda O!, x^P) \& (\lambda O!, y^P) \text{ in } v]$ 
assume  $[(\lambda z . z^P =_E x^P) \neq (\lambda z . z^P =_E y^P) \text{ in } v]$ 
moreover {
  assume  $[x^P = y^P \text{ in } v]$ 
  hence  $[(\lambda z . z^P =_E x^P) = (\lambda z . z^P =_E y^P) \text{ in } v]$ 
  using id-eq-1 l-identity[axiom-instance, deduction, deduction]
  by fast
}
ultimately show  $[x^P \neq y^P \text{ in } v]$ 
using modus-tollens-1 CP by blast
qed

```

lemma ab-obey-1[PLM]:
 $[(\lambda A!, x^P) \& (\lambda A!, y^P)] \rightarrow ((\forall F . \llbracket x^P, F \rrbracket \equiv \llbracket y^P, F \rrbracket) \rightarrow x^P = y^P) \text{ in } v$
proof(rule CP; rule CP)
assume abs-xy: $[(\lambda A!, x^P) \& (\lambda A!, y^P) \text{ in } v]$
assume enc-equiv: $[\forall F . \llbracket x^P, F \rrbracket \equiv \llbracket y^P, F \rrbracket \text{ in } v]$
{
fix P
have $[\llbracket x^P, P \rrbracket \equiv \llbracket y^P, P \rrbracket \text{ in } v]$
using enc-equiv **by** (rule $\forall E$)
hence $[\Box(\llbracket x^P, P \rrbracket \equiv \llbracket y^P, P \rrbracket) \text{ in } v]$
using en-eq-2 intro-elim-6-e intro-elim-6-f
 en-eq-5[equiv-rl] **by** meson
}
hence $[\Box(\forall F . \llbracket x^P, F \rrbracket \equiv \llbracket y^P, F \rrbracket) \text{ in } v]$
using BF[deduction] $\forall I$ **by** fast
thus $[x^P = y^P \text{ in } v]$
unfolding identity-defs
using $\forall I(2)$ abs-xy &I **by** presburger
qed

lemma ab-obey-2[PLM]:
 $[(\lambda A!, x^P) \& (\lambda A!, y^P)] \rightarrow ((\exists F . \llbracket x^P, F \rrbracket \& \neg \llbracket y^P, F \rrbracket) \rightarrow x^P \neq y^P) \text{ in } v$
proof(rule CP; rule CP)
assume abs-xy: $[(\lambda A!, x^P) \& (\lambda A!, y^P) \text{ in } v]$
assume $[\exists F . \llbracket x^P, F \rrbracket \& \neg \llbracket y^P, F \rrbracket \text{ in } v]$
then obtain P **where** P-prop:
 $[\llbracket x^P, P \rrbracket \& \neg \llbracket y^P, P \rrbracket \text{ in } v]$
by (rule $\exists E$)
{
assume $[x^P = y^P \text{ in } v]$
hence $[\llbracket x^P, P \rrbracket \equiv \llbracket y^P, P \rrbracket \text{ in } v]$
using l-identity[axiom-instance, deduction, deduction]
 oth-class-taut-4-a **by** fast
hence $[\llbracket y^P, P \rrbracket \text{ in } v]$
}

```

    using P-prop[conj1] by (rule  $\equiv E$ )
  }
  thus  $[x^P \neq y^P \text{ in } v]$ 
    using P-prop[conj2] modus-tollens-1 CP by blast
qed

```

```

lemma ordnecfail[PLM]:
   $[\Box(O!, x^P) \rightarrow \Box(\neg(\exists F. \llbracket x^P, F \rrbracket)) \text{ in } v]$ 
proof (rule CP)
  assume  $[\Box(O!, x^P) \text{ in } v]$ 
  hence  $[\Box(O!, x^P) \text{ in } v]$ 
    using oa-facts-1[deduction] by simp
  moreover hence  $[\Box(\Box(O!, x^P) \rightarrow (\neg(\exists F. \llbracket x^P, F \rrbracket))) \text{ in } v]$ 
    using nocoder[axiom-necessitation, axiom-instance] by simp
  ultimately show  $[\Box(\neg(\exists F. \llbracket x^P, F \rrbracket)) \text{ in } v]$ 
    using qml-1[axiom-instance, deduction, deduction] by fast
qed

```

```

lemma o-objects-exist-1[PLM]:
   $[\Diamond(\exists x. \Box(E!, x^P)) \text{ in } v]$ 
proof -
  have  $[\Diamond(\exists x. \Box(E!, x^P) \ \& \ \Diamond(\neg\Box(E!, x^P))) \text{ in } v]$ 
    using qml-4[axiom-instance, conj1] .
  hence  $[\Diamond((\exists x. \Box(E!, x^P)) \ \& \ (\exists x. \Diamond(\neg\Box(E!, x^P)))) \text{ in } v]$ 
    using sign-S5-thm-3[deduction] by fast
  hence  $[\Diamond(\exists x. \Box(E!, x^P)) \ \& \ \Diamond(\exists x. \Diamond(\neg\Box(E!, x^P))) \text{ in } v]$ 
    using KBasic2-8[deduction] by blast
  thus ?thesis using &E by blast
qed

```

```

lemma o-objects-exist-2[PLM]:
   $[\Box(\exists x. \Box(O!, x^P)) \text{ in } v]$ 
  apply (rule RN) unfolding Ordinary-def
  apply (PLM-subst1-method  $\lambda x. \Diamond\Box(E!, x^P) \ \lambda x. \Box(\lambda y. \Diamond\Box(E!, y^P), x^P)$ )
  apply (rule beta-C-meta-1[equiv-sym], rule IsPropositional-intros)
  using o-objects-exist-1 BF $\Diamond$ [deduction] by blast

```

```

lemma o-objects-exist-3[PLM]:
   $[\Box(\neg(\forall x. \Box(A!, x^P))) \text{ in } v]$ 
  apply (PLM-subst-method  $(\exists x. \neg\Box(A!, x^P)) \neg(\forall x. \Box(A!, x^P))$ )
    using cqt-further-2[equiv-sym] apply fast
  apply (PLM-subst1-method  $\lambda x. \Box(O!, x^P) \ \lambda x. \neg\Box(A!, x^P)$ )
  using oa-contingent-2 o-objects-exist-2 by auto

```

```

lemma a-objects-exist-1[PLM]:
   $[\Box(\exists x. \Box(A!, x^P)) \text{ in } v]$ 
proof -
  {
    fix v
    have  $[\exists x. \Box(A!, x^P) \ \& \ (\forall F. \llbracket x^P, F \rrbracket \equiv (F = F)) \text{ in } v]$ 
      using A-objects[axiom-instance] by simp
    hence  $[\exists x. \Box(A!, x^P) \text{ in } v]$ 
      using cqt-further-5[deduction, conj1] by fast
  }
  thus ?thesis by (rule RN)
qed

```

```

lemma a-objects-exist-2[PLM]:
   $[\Box(\neg(\forall x. \Box(O!, x^P))) \text{ in } v]$ 
  apply (PLM-subst-method  $(\exists x. \neg\Box(O!, x^P)) \neg(\forall x. \Box(O!, x^P))$ )
    using cqt-further-2[equiv-sym] apply fast
  apply (PLM-subst1-method  $\lambda x. \Box(A!, x^P) \ \lambda x. \neg\Box(O!, x^P)$ )
  using oa-contingent-3 a-objects-exist-1 by auto

```



```

lemma a-objects-exist-3[PLM]:
  [ $\Box(\neg(\forall x . \langle E!, x^P \rangle))$  in v]
proof –
  {
    fix v
    have [ $\exists x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv (F = F))$  in v]
      using A-objects[axiom-instance] by simp
    hence [ $\exists x . \langle A!, x^P \rangle$  in v]
      using cqt-further-5[deduction, conj1] by fast
    then obtain a where
      [ $\langle A!, a^P \rangle$  in v]
      by (rule  $\exists E$ )
    hence [ $\neg(\Diamond \langle E!, a^P \rangle)$  in v]
      unfolding Abstract-def
      using beta-C-meta-1[equiv-lr] IsPropositional-intros
      by fast
    hence [ $(\neg \langle E!, a^P \rangle)$  in v]
      using KBasic2-4[equiv-rl] qml-2[axiom-instance, deduction]
      by simp
    hence [ $\neg(\forall x . \langle E!, x^P \rangle)$  in v]
      using  $\exists I$  cqt-further-2[equiv-rl]
      by fast
  }
  thus ?thesis
  by (rule RN)
qed

lemma encoders-are-abstract[PLM]:
  [ $(\exists F . \langle x^P, F \rangle) \rightarrow \langle A!, x^P \rangle$  in v]
  using nocoder[axiom-instance] contraposition-2
    oa-contingent-2[THEN oth-class-taut-5-d[equiv-lr], equiv-lr]
    useful-tautologies-1[deduction]
    vdash-properties-10 CP by metis

lemma A-objects-unique[PLM]:
  [ $\exists! x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F)$  in v]
  proof –
    have [ $\exists x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F)$  in v]
      using A-objects[axiom-instance] by simp
    then obtain a where a-prop:
      [ $\langle A!, a^P \rangle \ \& \ (\forall F . \langle a^P, F \rangle \equiv \varphi F)$  in v] by (rule  $\exists E$ )
    moreover have [ $\forall y . \langle A!, y^P \rangle \ \& \ (\forall F . \langle y^P, F \rangle \equiv \varphi F) \rightarrow (y = a)$  in v]
      proof (rule  $\forall I$ ; rule CP)
        fix b
        assume b-prop: [ $\langle A!, b^P \rangle \ \& \ (\forall F . \langle b^P, F \rangle \equiv \varphi F)$  in v]
        {
          fix P
          have [ $\langle b^P, P \rangle \equiv \langle a^P, P \rangle$  in v]
            using a-prop[conj2] b-prop[conj2]  $\equiv I \equiv E(1) \equiv E(2)$ 
            CP vdash-properties-10  $\forall E$  by metis
        }
        hence [ $\forall F . \langle b^P, F \rangle \equiv \langle a^P, F \rangle$  in v]
          using  $\forall I$  by fast
        thus [ $b = a$  in v]
          unfolding identity-v-def
          using ab-obey-1[deduction, deduction]
            a-prop[conj1] b-prop[conj1]  $\&I$  by blast
      }
    qed
  ultimately show ?thesis
  unfolding exists-unique-def
  using  $\&I \exists I$  by fast
qed

```

lemma *obj-oth-1*[PLM]:
 $[\exists! x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \langle F, y^P \rangle)] \text{ in } v]$
using *A-objects-unique* .

lemma *obj-oth-2*[PLM]:
 $[\exists! x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv (\langle F, y^P \rangle \ \& \ \langle F, z^P \rangle))] \text{ in } v]$
using *A-objects-unique* .

lemma *obj-oth-3*[PLM]:
 $[\exists! x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv (\langle F, y^P \rangle \vee \langle F, z^P \rangle))] \text{ in } v]$
using *A-objects-unique* .

lemma *obj-oth-4*[PLM]:
 $[\exists! x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv (\Box \langle F, y^P \rangle))] \text{ in } v]$
using *A-objects-unique* .

lemma *obj-oth-5*[PLM]:
 $[\exists! x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv (F = G))] \text{ in } v]$
using *A-objects-unique* .

lemma *obj-oth-6*[PLM]:
 $[\exists! x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \Box(\forall y . \langle G, y^P \rangle \rightarrow \langle F, y^P \rangle))] \text{ in } v]$
using *A-objects-unique* .

lemma *A-Exists-1*[PLM]:
 $[\mathcal{A}(\exists! x :: ('a :: id-act) . \varphi x) \equiv (\exists! x . \mathcal{A}(\varphi x))] \text{ in } v]$
unfolding *exists-unique-def*
proof (*rule* $\equiv I$; *rule* *CP*)
assume $[\mathcal{A}(\exists \alpha . \varphi \alpha \ \& \ (\forall \beta . \varphi \beta \rightarrow \beta = \alpha))] \text{ in } v]$
hence $[\exists \alpha . \mathcal{A}(\varphi \alpha \ \& \ (\forall \beta . \varphi \beta \rightarrow \beta = \alpha))] \text{ in } v]$
using *Act-Basic-11*[*equiv-lr*] **by** *blast*
then obtain α **where**
 $[\mathcal{A}(\varphi \alpha \ \& \ (\forall \beta . \varphi \beta \rightarrow \beta = \alpha))] \text{ in } v]$
by (*rule* $\exists E$)
hence *1*: $[\mathcal{A}(\varphi \alpha) \ \& \ \mathcal{A}(\forall \beta . \varphi \beta \rightarrow \beta = \alpha)] \text{ in } v]$
using *Act-Basic-2*[*equiv-lr*] **by** *blast*
find-theorems $\mathcal{A}(\varphi \alpha \rightarrow \beta = \alpha)$
have *2*: $[\forall \beta . \mathcal{A}(\varphi \beta \rightarrow \beta = \alpha)] \text{ in } v]$
using *1*[*conj2*] *logic-actual-nec-3*[*axiom-instance*, *equiv-lr*] **by** *blast*
{
fix β
have $[\mathcal{A}(\varphi \beta \rightarrow \beta = \alpha)] \text{ in } v]$
using *2* **by** (*rule* $\forall E$)
hence $[\mathcal{A}(\varphi \beta) \rightarrow (\beta = \alpha)] \text{ in } v]$
using *logic-actual-nec-2*[*axiom-instance*, *equiv-lr*, *deduction*]
id-act-3[*equiv-rl*] *CP* **by** *blast*
}
hence $[\forall \beta . \mathcal{A}(\varphi \beta) \rightarrow (\beta = \alpha)] \text{ in } v]$
by (*rule* $\forall I$)
thus $[\exists \alpha . \mathcal{A} \varphi \alpha \ \& \ (\forall \beta . \mathcal{A} \varphi \beta \rightarrow \beta = \alpha)] \text{ in } v]$
using *1*[*conj1*] $\& I \exists I$ **by** *fast*
next
assume $[\exists \alpha . \mathcal{A} \varphi \alpha \ \& \ (\forall \beta . \mathcal{A} \varphi \beta \rightarrow \beta = \alpha)] \text{ in } v]$
then obtain α **where** *1*:
 $[\mathcal{A} \varphi \alpha \ \& \ (\forall \beta . \mathcal{A} \varphi \beta \rightarrow \beta = \alpha)] \text{ in } v]$
by (*rule* $\exists E$)
{
fix β
have $[\mathcal{A}(\varphi \beta) \rightarrow \beta = \alpha] \text{ in } v]$
using *1*[*conj2*] **by** (*rule* $\forall E$)
hence $[\mathcal{A}(\varphi \beta \rightarrow \beta = \alpha)] \text{ in } v]$
using *logic-actual-nec-2*[*axiom-instance*, *equiv-rl*] *id-act-3*[*equiv-lr*]
}

```

vdash-properties-10 CP by blast
}
hence  $[\forall \beta . \mathcal{A}(\varphi \beta \rightarrow \beta = \alpha) \text{ in } v]$ 
  by (rule  $\forall I$ )
hence  $[\mathcal{A}(\forall \beta . \varphi \beta \rightarrow \beta = \alpha) \text{ in } v]$ 
  using logic-actual-nec-3[axiom-instance, equiv-rl] by fast
hence  $[\mathcal{A}(\varphi \alpha \ \& \ (\forall \beta . \varphi \beta \rightarrow \beta = \alpha)) \text{ in } v]$ 
  using 1[conj1] Act-Basic-2[equiv-rl] &I by blast
hence  $[\exists \alpha . \mathcal{A}(\varphi \alpha \ \& \ (\forall \beta . \varphi \beta \rightarrow \beta = \alpha)) \text{ in } v]$ 
  using  $\exists I$  by fast
thus  $[\mathcal{A}(\exists \alpha . \varphi \alpha \ \& \ (\forall \beta . \varphi \beta \rightarrow \beta = \alpha)) \text{ in } v]$ 
  using Act-Basic-11[equiv-rl] by fast
qed

```

lemma *A-Exists-2*[PLM]:
 $[(\exists y . y^P = (\iota x . \varphi x)) \equiv \mathcal{A}(\exists !x . \varphi x) \text{ in } v]$
 using actual-desc-1 A-Exists-1[equiv-sym]
 intro-elim-6-e by blast

lemma *A-descriptions*[PLM]:
 $[\exists y . y^P = (\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F)) \text{ in } v]$
 using A-objects-unique[THEN RN, THEN nec-imp-act[deduction]]
 A-Exists-2[equiv-rl] by auto

lemma *thm-can-terms2*[PLM]:
 $[(y^P = (\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F)))$
 $\rightarrow ((\langle A!, y^P \rangle \ \& \ (\forall F . \langle y^P, F \rangle \equiv \varphi F)) \text{ in } dw)]$
 using *y-in-2* by auto

lemma *can-ab2*[PLM]:
 $[(y^P = (\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F))) \rightarrow \langle A!, y^P \rangle \text{ in } v]$
 proof (rule CP)
 assume $[y^P = (\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F)) \text{ in } v]$
 hence $[\mathcal{A}(\langle A!, y^P \rangle \ \& \ \mathcal{A}(\forall F . \langle y^P, F \rangle \equiv \varphi F) \text{ in } v)]$
 using nec-hintikka-scheme[equiv-lr, conj1]
 Act-Basic-2[equiv-lr] by blast
 thus $[\langle A!, y^P \rangle \text{ in } v]$
 using oa-facts-8[equiv-rl] &E by blast
 qed

lemma *desc-encode*[PLM]:
 $[(\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F), G \equiv \varphi G \text{ in } dw)]$
 proof –
 obtain *a* where
 $[a^P = (\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv \varphi F)) \text{ in } dw]$
 using A-descriptions by (rule $\exists E$)
 moreover hence $[\langle a^P, G \rangle \equiv \varphi G \text{ in } dw]$
 using hintikka[equiv-lr, conj1] &E $\forall E$ by fast
 ultimately show ?thesis
 using l-identity[axiom-instance, deduction, deduction] by fast
 qed

TODO 4. Have another look at remark 185.

```

notepad
begin
let ?x =  $\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv (\exists q . q \ \& \ F = (\lambda y . q)))$ 
have  $[(\exists p . \text{ContingentlyTrue } p) \text{ in } dw]$ 
  using cont-tf-thm-3 by auto
then obtain  $p_1$  where  $[\text{ContingentlyTrue } p_1 \text{ in } dw]$  by (rule  $\exists E$ )
hence  $[p_1 \text{ in } dw]$  unfolding ContingentlyTrue-def using &E by fast
hence  $[p_1 \ \& \ (\lambda y . p_1) = (\lambda y . p_1) \text{ in } dw]$  using &I id-eq-1 by fast
hence  $[\exists q . q \ \& \ (\lambda y . p_1) = (\lambda y . q) \text{ in } dw]$  using  $\exists I$  by fast
moreover have  $[\langle ?x, \lambda y . p_1 \rangle \equiv (\exists q . q \ \& \ (\lambda y . p_1) = (\lambda y . q)) \text{ in } dw]$ 

```

```

    using desc-encode by fast
ultimately have [ $\llbracket ?x, \lambda y . p_1 \rrbracket$  in  $dw$ ]
    using  $\equiv E$  by blast
hence [ $\llbracket ?x, \lambda y . p_1 \rrbracket$  in  $dw$ ]
    using encoding[axiom-instance,deduction] by fast
hence  $\forall v . \llbracket ?x, \lambda y . p_1 \rrbracket$  in  $v$ ]
    using Semantics.T6 by simp
end

lemma desc-nec-encode[PLM]:
  [ $\llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi F), G \rrbracket \equiv \mathcal{A}(\varphi G)$  in  $v$ ]
proof -
  obtain  $a$  where
    [ $a^P = (\iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi F))$  in  $v$ ]
    using A-descriptions by (rule  $\exists E$ )
  moreover {
    hence [ $\mathcal{A}(\langle A!, a^P \rangle \ \& \ (\forall F . \llbracket a^P, F \rrbracket \equiv \varphi F))$  in  $v$ ]
      using nec-hintikka-scheme[equiv-lr, conj1] by fast
    hence [ $\mathcal{A}(\forall F . \llbracket a^P, F \rrbracket \equiv \varphi F)$  in  $v$ ]
      using Act-Basic-2[equiv-lr,conj2] by blast
    hence [ $\forall F . \mathcal{A}(\llbracket a^P, F \rrbracket \equiv \varphi F)$  in  $v$ ]
      using logic-actual-nec-3[axiom-instance, equiv-lr] by blast
    hence [ $\mathcal{A}(\llbracket a^P, G \rrbracket \equiv \varphi G)$  in  $v$ ]
      using  $\forall E$  by fast
    hence [ $\mathcal{A}\llbracket a^P, G \rrbracket \equiv \mathcal{A}(\varphi G)$  in  $v$ ]
      using Act-Basic-5[equiv-lr] by fast
    hence [ $\llbracket a^P, G \rrbracket \equiv \mathcal{A}(\varphi G)$  in  $v$ ]
      using en-eq-10[equiv-sym] intro-elim-6-e by blast
  }
  ultimately show ?thesis
    using l-identity[axiom-instance, deduction, deduction] by fast
qed

```

```

notepad
begin
  fix  $v$ 
  let  $?x = \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv (\exists q . q \ \& \ F = (\lambda y . q)))$ 
  have [ $\llbracket \exists p . \text{ContingentlyTrue } p \rrbracket$  in  $v$ ]
    using cont-tf-thm-3 RN by auto
  hence [ $\mathcal{A}(\exists p . \text{ContingentlyTrue } p)$  in  $v$ ]
    using nec-imp-act[deduction] by simp
  hence [ $\exists p . \mathcal{A}(\text{ContingentlyTrue } p)$  in  $v$ ]
    using Act-Basic-11[equiv-lr] by auto
  then obtain  $p_1$  where
    [ $\mathcal{A}(\text{ContingentlyTrue } p_1)$  in  $v$ ]
    by (rule  $\exists E$ )
  hence [ $\mathcal{A}p_1$  in  $v$ ]
    unfolding ContingentlyTrue-def
    using Act-Basic-2[equiv-lr] &E by fast
  hence [ $\mathcal{A}p_1 \ \& \ \mathcal{A}((\lambda y . p_1) = (\lambda y . p_1))$  in  $v$ ]
    using &I id-eq-1[THEN RN, THEN nec-imp-act[deduction]] by fast
  hence [ $\mathcal{A}(p_1 \ \& \ (\lambda y . p_1) = (\lambda y . p_1))$  in  $v$ ]
    using Act-Basic-2[equiv-rl] by fast
  hence [ $\exists q . \mathcal{A}(q \ \& \ (\lambda y . p_1) = (\lambda y . q))$  in  $v$ ]
    using  $\exists I$  by fast
  hence [ $\mathcal{A}(\exists q . q \ \& \ (\lambda y . p_1) = (\lambda y . q))$  in  $v$ ]
    using Act-Basic-11[equiv-rl] by fast
  moreover have [ $\llbracket ?x, \lambda y . p_1 \rrbracket \equiv \mathcal{A}(\exists q . q \ \& \ (\lambda y . p_1) = (\lambda y . q))$  in  $v$ ]
    using desc-nec-encode by fast
  ultimately have [ $\llbracket ?x, \lambda y . p_1 \rrbracket$  in  $v$ ]
    using  $\equiv E$  by blast
end

```

lemma *Box-desc-encode-1*[PLM]:
 $\boxed{(\varphi \ G \rightarrow \llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F)) , G \rrbracket}$ in v
proof (*rule CP*)
 assume $\boxed{(\varphi \ G)}$ in v
 hence $\llbracket \mathcal{A}(\varphi \ G) \rrbracket$ in v
 using *nec-imp-act*[deduction] **by** *auto*
 thus $\llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F) , G \rrbracket$ in v
 using *desc-nec-encode*[equiv-rl] **by** *simp*
qed

lemma *Box-desc-encode-2*[PLM]:
 $\boxed{(\varphi \ G \rightarrow \boxed{\llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F)) , G \rrbracket \equiv \varphi \ G}$ in v
proof (*rule CP*)
 assume a : $\boxed{(\varphi \ G)}$ in v
 hence $\boxed{\llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F) , G \rrbracket \rightarrow \varphi \ G}$ in v
 using *KBasic-1*[deduction] **by** *simp*
 moreover {
 have $\llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F) , G \rrbracket$ in v
 using *a Box-desc-encode-1*[deduction] **by** *auto*
 hence $\boxed{\llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F) , G \rrbracket}$ in v
 using *encoding*[axiom-instance, deduction] **by** *blast*
 hence $\boxed{(\varphi \ G \rightarrow \llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F)) , G \rrbracket}$ in v
 using *KBasic-1*[deduction] **by** *simp*
 }
 ultimately show $\boxed{\llbracket \iota x . \langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F) , G \rrbracket \equiv \varphi \ G}$ in v
 using *&I KBasic-4*[equiv-rl] **by** *blast*
qed

lemma *box-phi-a-1*[PLM]:
 assumes $\boxed{(\forall F . \varphi \ F \rightarrow \boxed{\varphi \ F})}$ in v
 shows $\llbracket (\langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F)) \rightarrow \boxed{\langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F)} \rrbracket$ in v
proof (*rule CP*)
 assume a : $\llbracket (\langle A!, x^P \rangle \ \& \ (\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F)) \rrbracket$ in v
 have $\boxed{\langle A!, x^P \rangle}$ in v
 using *oa-facts-2*[deduction] *a*[conj1] **by** *auto*
 moreover have $\boxed{(\forall F . \llbracket x^P, F \rrbracket \equiv \varphi \ F)}$ in v
proof (*rule BF*[deduction]; *rule $\forall I$*)
 fix F
 have ϑ : $\boxed{(\varphi \ F \rightarrow \boxed{\varphi \ F})}$ in v
 using *assms*[THEN CBF[deduction]] **by** (*rule $\forall E$*)
 moreover have $\boxed{(\llbracket x^P, F \rrbracket \rightarrow \boxed{\llbracket x^P, F \rrbracket})}$ in v
 using *encoding*[axiom-necessitation, axiom-instance] **by** *simp*
 moreover have $\boxed{\llbracket x^P, F \rrbracket \equiv \boxed{\varphi \ F}}$ in v
proof (*rule $\equiv I$* ; *rule CP*)
 assume $\boxed{\llbracket x^P, F \rrbracket}$ in v
 hence $\llbracket \llbracket x^P, F \rrbracket \rrbracket$ in v
 using *qml-2*[axiom-instance, deduction] **by** *blast*
 hence $\varphi \ F$ in v
 using *a*[conj2] $\forall E \equiv E$ **by** *blast*
 thus $\boxed{(\varphi \ F)}$ in v
 using ϑ [THEN *qml-2*[axiom-instance, deduction], deduction] **by** *simp*
 next
 assume $\boxed{(\varphi \ F)}$ in v
 hence $\varphi \ F$ in v
 using *qml-2*[axiom-instance, deduction] **by** *blast*
 hence $\llbracket \llbracket x^P, F \rrbracket \rrbracket$ in v
 using *a*[conj2] $\forall E \equiv E$ **by** *blast*
 thus $\boxed{\llbracket \llbracket x^P, F \rrbracket \rrbracket}$ in v
 using *encoding*[axiom-instance, deduction] **by** *simp*
qed
 ultimately show $\boxed{\llbracket \llbracket x^P, F \rrbracket \rrbracket \equiv \varphi \ F}$ in v

```

    using sc-eq-box-box-3[deduction, deduction] &I by blast
  qed
  ultimately show  $[\Box((\lambda A!.x^P) \ \& \ (\forall F. \llbracket x^P, F \rrbracket \equiv \varphi F)) \text{ in } v]$ 
    using &I KBasic-3[equiv-rl] by blast
  qed

```

TODO 5. The proof of the following theorem seems to incorrectly reference (88) instead of (108).

```

lemma box-phi-a-2[PLM]:
  assumes  $[\Box(\forall F. \varphi F \rightarrow \Box(\varphi F)) \text{ in } v]$ 
  shows  $[y^P = (\lambda x. \llbracket A!, x^P \rrbracket \ \& \ (\forall F. \llbracket x^P, F \rrbracket \equiv \varphi F)) \text{ in } v]$ 
     $\rightarrow ((\lambda A!, y^P) \ \& \ (\forall F. \llbracket y^P, F \rrbracket \equiv \varphi F)) \text{ in } v]$ 
  proof -
    let  $? \psi = \lambda x. \llbracket A!, x^P \rrbracket \ \& \ (\forall F. \llbracket x^P, F \rrbracket \equiv \varphi F)$ 
    have  $[\forall x. ? \psi x \rightarrow \Box(? \psi x) \text{ in } v]$ 
      using box-phi-a-1[OF assms]  $\forall I$  by fast
    hence  $[(\exists! x. ? \psi x) \rightarrow (\forall y. y^P = (\lambda x. ? \psi x) \rightarrow ? \psi y) \text{ in } v]$ 
      using unique-box-desc[deduction] by fast
    hence  $[(\forall y. y^P = (\lambda x. ? \psi x) \rightarrow ? \psi y) \text{ in } v]$ 
      using A-objects-unique modus-ponens by blast
    thus ?thesis by (rule  $\forall E$ )
  qed

```

```

lemma box-phi-a-3[PLM]:
  assumes  $[\Box(\forall F. \varphi F \rightarrow \Box(\varphi F)) \text{ in } v]$ 
  shows  $[\llbracket \lambda x. \llbracket A!, x^P \rrbracket \ \& \ (\forall F. \llbracket x^P, F \rrbracket \equiv \varphi F), G \rrbracket \equiv \varphi G \text{ in } v]$ 
  proof -
    obtain a where
       $[a^P = (\lambda x. \llbracket A!, x^P \rrbracket \ \& \ (\forall F. \llbracket x^P, F \rrbracket \equiv \varphi F)) \text{ in } v]$ 
      using A-descriptions by (rule  $\exists E$ )
    moreover {
      hence  $[(\forall F. \llbracket a^P, F \rrbracket \equiv \varphi F) \text{ in } v]$ 
        using box-phi-a-2[OF assms, deduction, conj2] by blast
      hence  $[\llbracket a^P, G \rrbracket \equiv \varphi G \text{ in } v] \text{ by (rule } \forall E)$ 
    }
    ultimately show ?thesis
      using l-identity[axiom-instance, deduction, deduction] by fast
  qed

```

```

lemma null-uni-uniq-1[PLM]:
   $[(\exists! x. \text{Null } (x^P)) \text{ in } v]$ 
  proof -
    have  $[(\exists x. \llbracket A!, x^P \rrbracket \ \& \ (\forall F. \llbracket x^P, F \rrbracket \equiv (F \neq F)) \text{ in } v]$ 
      using A-objects[axiom-instance] by simp
    then obtain a where a-prop:
       $[\llbracket A!, a^P \rrbracket \ \& \ (\forall F. \llbracket a^P, F \rrbracket \equiv (F \neq F)) \text{ in } v]$ 
      by (rule  $\exists E$ )
    have 1:  $[\llbracket A!, a^P \rrbracket \ \& \ (\neg(\exists F. \llbracket a^P, F \rrbracket)) \text{ in } v]$ 
      using a-prop[conj1] apply (rule &I)
    proof -
      {
        assume  $[\exists F. \llbracket a^P, F \rrbracket \text{ in } v]$ 
        then obtain P where
           $[\llbracket a^P, P \rrbracket \text{ in } v] \text{ by (rule } \exists E)$ 
        hence  $[P \neq P \text{ in } v]$ 
          using a-prop[conj2, THEN  $\forall E$ , equiv-lr] by simp
        hence  $[\neg(\exists F. \llbracket a^P, F \rrbracket) \text{ in } v]$ 
          using id-eq-1 reductio-aa-1 by fast
      }
      thus  $[\neg(\exists F. \llbracket a^P, F \rrbracket) \text{ in } v]$ 
        using reductio-aa-1 by blast
    qed
    moreover have  $[\forall y. ((\llbracket A!, y^P \rrbracket \ \& \ (\neg(\exists F. \llbracket y^P, F \rrbracket))) \rightarrow y = a) \text{ in } v]$ 

```

```

proof (rule  $\forall I$ ; rule CP)
  fix  $y$ 
  assume 2:  $[\langle A!, y^P \rangle \ \& \ (\neg(\exists F . \langle y^P, F \rangle))] \text{ in } v$ 
  have  $[\forall F . \langle y^P, F \rangle \equiv \langle a^P, F \rangle] \text{ in } v$ 
    using cqt-further-12[deduction] 1[conj2] 2[conj2] &I by blast
  thus  $[y = a \text{ in } v]$ 
    using ab-obey-1[deduction, deduction]
    &I[OF 2[conj1] 1[conj1]] identity- $\nu$ -def by presburger
  qed
ultimately show ?thesis
  using &I  $\exists I$ 
  unfolding Null-def exists-unique-def by fast
qed

lemma null-uni-uniq-2[PLM]:
 $[\exists! x . \text{Universal } (x^P) \text{ in } v]$ 
proof –
  have  $[\exists x . \langle A!, x^P \rangle \ \& \ (\forall F . \langle x^P, F \rangle \equiv (F = F))] \text{ in } v$ 
    using A-objects[axiom-instance] by simp
  then obtain  $a$  where a-prop:
 $[\langle A!, a^P \rangle \ \& \ (\forall F . \langle a^P, F \rangle \equiv (F = F))] \text{ in } v$ 
  by (rule  $\exists E$ )
  have 1:  $[\langle A!, a^P \rangle \ \& \ (\forall F . \langle a^P, F \rangle)] \text{ in } v$ 
    using a-prop[conj1] apply (rule &I)
    using  $\forall I$  a-prop[conj2, THEN  $\forall E$ , equiv-rl] id-eq-1 by blast
  moreover have  $[\forall y . (\langle A!, y^P \rangle \ \& \ (\forall F . \langle y^P, F \rangle)) \rightarrow y = a \text{ in } v]$ 
    proof (rule  $\forall I$ ; rule CP)
      fix  $y$ 
      assume 2:  $[\langle A!, y^P \rangle \ \& \ (\forall F . \langle y^P, F \rangle)] \text{ in } v$ 
      have  $[\forall F . \langle y^P, F \rangle \equiv \langle a^P, F \rangle] \text{ in } v$ 
        using cqt-further-11[deduction] 1[conj2] 2[conj2] &I by blast
      thus  $[y = a \text{ in } v]$ 
        using ab-obey-1[deduction, deduction]
        &I[OF 2[conj1] 1[conj1]] identity- $\nu$ -def
        by presburger
      qed
    ultimately show ?thesis
    using &I  $\exists I$ 
    unfolding Universal-def exists-unique-def by fast
  qed

lemma null-uni-uniq-3[PLM]:
 $[\exists y . y^P = (\iota x . \text{Null } (x^P)) \text{ in } v]$ 
using null-uni-uniq-1[THEN RN, THEN nec-imp-act[deduction]]
  A-Exists-2[equiv-rl] by auto

lemma null-uni-uniq-4[PLM]:
 $[\exists y . y^P = (\iota x . \text{Universal } (x^P)) \text{ in } v]$ 
using null-uni-uniq-2[THEN RN, THEN nec-imp-act[deduction]]
  A-Exists-2[equiv-rl] by auto

lemma null-uni-facts-1[PLM]:
 $[\text{Null } (x^P) \rightarrow \Box(\text{Null } (x^P)) \text{ in } v]$ 
proof (rule CP)
  assume  $[\text{Null } (x^P) \text{ in } v]$ 
  hence 1:  $[\langle A!, x^P \rangle \ \& \ (\neg(\exists F . \langle x^P, F \rangle))] \text{ in } v$ 
    unfolding Null-def .
  have  $[\Box \langle A!, x^P \rangle] \text{ in } v$ 
    using 1[conj1] oa-facts-2[deduction] by simp
  moreover have  $[\Box(\neg(\exists F . \langle x^P, F \rangle))] \text{ in } v$ 
    proof –
    {
      assume  $[\neg\Box(\neg(\exists F . \langle x^P, F \rangle))] \text{ in } v$ 

```

hence $[\Diamond(\exists F . \llbracket x^P, F \rrbracket) \text{ in } v]$
 unfolding *diamond-def* .
 hence $[\exists F . \Diamond \llbracket x^P, F \rrbracket \text{ in } v]$
 using *BF* \Diamond [*deduction*] **by** *blast*
 then obtain P where $[\Diamond \llbracket x^P, P \rrbracket \text{ in } v]$
 by (*rule* $\exists E$)
 hence $[\llbracket x^P, P \rrbracket \text{ in } v]$
 using *en-eq-3*[*equiv-lr*] **by** *simp*
 hence $[\exists F . \llbracket x^P, F \rrbracket \text{ in } v]$
 using $\exists I$ **by** *blast*
 }
 thus *?thesis*
 using *1*[*conj2*] *modus-tollens-1 CP*
useful-tautologies-1[*deduction*] **by** *metis*
 qed
 ultimately show $[\Box \text{Null}(x^P) \text{ in } v]$
 unfolding *Null-def*
 using $\&I$ *KBasic-3*[*equiv-rl*] **by** *blast*
 qed

lemma *null-uni-facts-2*[*PLM*]:

$[\text{Universal}(x^P) \rightarrow \Box(\text{Universal}(x^P)) \text{ in } v]$
proof (*rule CP*)
 assume $[\text{Universal}(x^P) \text{ in } v]$
 hence $1: [\Box(A!, x^P) \ \& \ (\forall F . \llbracket x^P, F \rrbracket) \text{ in } v]$
 unfolding *Universal-def* .
 have $[\Box(A!, x^P) \text{ in } v]$
 using *1*[*conj1*] *oa-facts-2*[*deduction*] **by** *simp*
 moreover have $[\Box(\forall F . \llbracket x^P, F \rrbracket) \text{ in } v]$
proof (*rule BF*[*deduction*]; *rule* $\forall I$)
 fix F
 have $[\llbracket x^P, F \rrbracket \text{ in } v]$
 using *1*[*conj2*] **by** (*rule* $\forall E$)
 thus $[\Box \llbracket x^P, F \rrbracket \text{ in } v]$
 using *encoding*[*axiom-instance*, *deduction*] **by** *auto*
 qed
 ultimately show $[\Box \text{Universal}(x^P) \text{ in } v]$
 unfolding *Universal-def*
 using $\&I$ *KBasic-3*[*equiv-rl*] **by** *blast*
 qed

lemma *null-uni-facts-3*[*PLM*]:

$[\text{Null}(\mathbf{a}_\emptyset) \text{ in } v]$
proof –
 let $? \psi = \lambda x . \text{Null } x$
 have $[(\exists! x . ? \psi(x^P)) \rightarrow (\forall y . y^P = (\iota x . ? \psi(x^P)) \rightarrow ? \psi(y^P))] \text{ in } v]$
 using *unique-box-desc*[*deduction*] *null-uni-facts-1*[*THEN* $\forall I$] **by** *fast*
 have $1: [(\forall y . y^P = (\iota x . ? \psi(x^P)) \rightarrow ? \psi(y^P)) \text{ in } v]$
 using *unique-box-desc*[*deduction*, *deduction*] *null-uni-uniq-1*
null-uni-facts-1[*THEN* $\forall I$] **by** *fast*
 have $[\exists y . y^P = (\mathbf{a}_\emptyset) \text{ in } v]$
 unfolding *NullObject-def* using *null-uni-uniq-3* .
 then obtain y where $[y^P = (\mathbf{a}_\emptyset) \text{ in } v]$
 by (*rule* $\exists E$)
 moreover hence $[? \psi(y^P) \text{ in } v]$
 using *1*[*THEN* $\forall E$, *deduction*] unfolding *NullObject-def* **by** *simp*
 ultimately show $[? \psi(\mathbf{a}_\emptyset) \text{ in } v]$
 using *l-identity*[*axiom-instance*, *deduction*, *deduction*] **by** *blast*
 qed

lemma *null-uni-facts-4*[*PLM*]:

$[\text{Universal}(\mathbf{a}_V) \text{ in } v]$
proof –

let $?ψ = λ x . Universal\ x$
have $[((\exists! x . ?ψ (x^P)) \rightarrow (\forall y . y^P = (\iota x . ?ψ (x^P)) \rightarrow ?ψ (y^P))) \text{ in } v]$
using *unique-box-desc*[deduction] *null-uni-facts-2*[*THEN* $\forall I$] **by** *fast*
have $1: [(\forall y . y^P = (\iota x . ?ψ (x^P)) \rightarrow ?ψ (y^P)) \text{ in } v]$
using *unique-box-desc*[deduction, deduction] *null-uni-uniq-2*
null-uni-facts-2[*THEN* $\forall I$] **by** *fast*
have $[\exists y . y^P = (a_V) \text{ in } v]$
unfolding *UniversalObject-def* **using** *null-uni-uniq-4* .
then obtain y **where** $[y^P = (a_V) \text{ in } v]$
by (*rule* $\exists E$)
moreover hence $[?ψ (y^P) \text{ in } v]$
using *1*[*THEN* $\forall E$, deduction]
unfolding *UniversalObject-def* **by** *simp*
ultimately show $[?ψ (a_V) \text{ in } v]$
using *l-identity*[*axiom-instance*, deduction, deduction] **by** *blast*
qed

lemma *aclassical-1*[*PLM*]:

$[\forall R . \exists x y . \langle A!, x^P \rangle \ \& \ \langle A!, y^P \rangle \ \& \ (x \neq y)$
 $\ \& \ (\lambda z . \langle R, z^P, x^P \rangle) = (\lambda z . \langle R, z^P, y^P \rangle) \text{ in } v]$
proof (*rule* $\forall I$)
fix R
obtain a **where** ϑ :
 $[\langle A!, a^P \rangle \ \& \ (\forall F . \langle a^P, F \rangle \equiv (\exists y . \langle A!, y^P \rangle$
 $\ \& \ F = (\lambda z . \langle R, z^P, y^P \rangle) \ \& \ \neg \langle y^P, F \rangle)) \text{ in } v]$
using *A-objects*[*axiom-instance*] **by** (*rule* $\exists E$)
{
assume $[\neg \langle a^P, (\lambda z . \langle R, z^P, a^P \rangle) \rangle \text{ in } v]$
hence $[\neg (\langle A!, a^P \rangle \ \& \ (\lambda z . \langle R, z^P, a^P \rangle) = (\lambda z . \langle R, z^P, a^P \rangle)$
 $\ \& \ \neg \langle a^P, (\lambda z . \langle R, z^P, a^P \rangle) \rangle) \text{ in } v]$
using ϑ [*conj2*, *THEN* $\forall E$, *THEN* *oth-class-taut-5-d*[*equiv-lr*], *equiv-lr*]
cqt-further-4[*equiv-lr*] $\forall E$ **by** *blast*
hence $[\langle A!, a^P \rangle \ \& \ (\lambda z . \langle R, z^P, a^P \rangle) = (\lambda z . \langle R, z^P, a^P \rangle)$
 $\rightarrow \langle a^P, (\lambda z . \langle R, z^P, a^P \rangle) \rangle \text{ in } v]$
apply *cut-tac* **by** *PLM-solver*
hence $[\langle a^P, (\lambda z . \langle R, z^P, a^P \rangle) \rangle \text{ in } v]$
using ϑ [*conj1*] *id-eq-1* $\&I$ *vdash-properties-10* **by** *fast*
}
hence $1: [\langle a^P, (\lambda z . \langle R, z^P, a^P \rangle) \rangle \text{ in } v]$
using *reductio-aa-1* *CP if-p-then-p* **by** *blast*
then obtain b **where** ξ :
 $[\langle A!, b^P \rangle \ \& \ (\lambda z . \langle R, z^P, a^P \rangle) = (\lambda z . \langle R, z^P, b^P \rangle)$
 $\ \& \ \neg \langle b^P, (\lambda z . \langle R, z^P, a^P \rangle) \rangle \text{ in } v]$
using ϑ [*conj2*, *THEN* $\forall E$, *equiv-lr*] $\exists E$ **by** *blast*
have $[a \neq b \text{ in } v]$
proof –
{
assume $[a = b \text{ in } v]$
hence $[\langle b^P, (\lambda z . \langle R, z^P, a^P \rangle) \rangle \text{ in } v]$
using *1* *l-identity*[*axiom-instance*, deduction, deduction] **by** *fast*
hence *?thesis*
using ξ [*conj2*] *reductio-aa-1* **by** *blast*
}
thus *?thesis* **using** *reductio-aa-1* **by** *blast*
qed
hence $[\langle A!, a^P \rangle \ \& \ \langle A!, b^P \rangle \ \& \ a \neq b$
 $\ \& \ (\lambda z . \langle R, z^P, a^P \rangle) = (\lambda z . \langle R, z^P, b^P \rangle) \text{ in } v]$
using ϑ [*conj1*] ξ [*conj1*, *conj1*] ξ [*conj1*, *conj2*] $\&I$ **by** *presburger*
hence $[\exists y . \langle A!, a^P \rangle \ \& \ \langle A!, y^P \rangle \ \& \ a \neq y$
 $\ \& \ (\lambda z . \langle R, z^P, a^P \rangle) = (\lambda z . \langle R, z^P, y^P \rangle) \text{ in } v]$
using $\exists I$ **by** *fast*
thus $[\exists x y . \langle A!, x^P \rangle \ \& \ \langle A!, y^P \rangle \ \& \ x \neq y$
 $\ \& \ (\lambda z . \langle R, z^P, x^P \rangle) = (\lambda z . \langle R, z^P, y^P \rangle) \text{ in } v]$

using $\exists I$ by fast
qed

lemma *aclassical-2*[PLM]:

$[\forall R . \exists x y . \langle A!, x^P \rangle \& \langle A!, y^P \rangle \& (x \neq y)$
 $\& (\lambda z . \langle R, x^P, z^P \rangle) = (\lambda z . \langle R, y^P, z^P \rangle) \text{ in } v]$
proof (rule $\forall I$)
 fix R
 obtain a where ϑ :
 $[\langle A!, a^P \rangle \& (\forall F . \langle a^P, F \rangle \equiv (\exists y . \langle A!, y^P \rangle$
 $\& F = (\lambda z . \langle R, y^P, z^P \rangle) \& \neg \langle y^P, F \rangle)) \text{ in } v]$
 using *A-objects*[*axiom-instance*] **by** (rule $\exists E$)
 {
 assume $[\neg \langle a^P, (\lambda z . \langle R, a^P, z^P \rangle) \rangle] \text{ in } v]$
 hence $[\neg(\langle A!, a^P \rangle \& (\lambda z . \langle R, a^P, z^P \rangle) = (\lambda z . \langle R, a^P, z^P \rangle)$
 $\& \neg \langle a^P, (\lambda z . \langle R, a^P, z^P \rangle) \rangle) \text{ in } v]$
 using $\vartheta[\text{conj2}, \text{THEN } \forall E, \text{THEN } \text{oth-class-taut-5-d}[\text{equiv-lr}], \text{equiv-lr}]$
 $\text{cqt-further-4}[\text{equiv-lr}] \forall E$ **by** blast
 hence $[\langle A!, a^P \rangle \& (\lambda z . \langle R, a^P, z^P \rangle) = (\lambda z . \langle R, a^P, z^P \rangle)$
 $\rightarrow \langle a^P, (\lambda z . \langle R, a^P, z^P \rangle) \rangle] \text{ in } v]$
 apply *cut-tac* **by** *PLM-solver*
 hence $[\langle a^P, (\lambda z . \langle R, a^P, z^P \rangle) \rangle] \text{ in } v]$
 using $\vartheta[\text{conj1}] \text{id-eq-1} \& I \text{vdash-properties-10}$ **by** fast
 }
 hence $1: [\langle a^P, (\lambda z . \langle R, a^P, z^P \rangle) \rangle] \text{ in } v]$
 using *reductio-aa-1 CP if-p-then-p* **by** blast
 then obtain b where ξ :
 $[\langle A!, b^P \rangle \& (\lambda z . \langle R, a^P, z^P \rangle) = (\lambda z . \langle R, b^P, z^P \rangle)$
 $\& \neg \langle b^P, (\lambda z . \langle R, a^P, z^P \rangle) \rangle] \text{ in } v]$
 using $\vartheta[\text{conj2}, \text{THEN } \forall E, \text{equiv-lr}] \exists E$ **by** blast
 have $[a \neq b \text{ in } v]$
proof –
 {
 assume $[a = b \text{ in } v]$
 hence $[\langle b^P, (\lambda z . \langle R, a^P, z^P \rangle) \rangle] \text{ in } v]$
 using *1 l-identity*[*axiom-instance, deduction, deduction*] **by** fast
 hence $?thesis$ using $\xi[\text{conj2}] \text{reductio-aa-1}$ **by** blast
 }
 thus $?thesis$ using $\xi[\text{conj2}] \text{reductio-aa-1}$ **by** blast
 qed
 hence $[\langle A!, a^P \rangle \& \langle A!, b^P \rangle \& a \neq b$
 $\& (\lambda z . \langle R, a^P, z^P \rangle) = (\lambda z . \langle R, b^P, z^P \rangle) \text{ in } v]$
 using $\vartheta[\text{conj1}] \xi[\text{conj1}, \text{conj1}] \xi[\text{conj1}, \text{conj2}] \& I$ **by** *presburger*
 hence $[\exists y . \langle A!, a^P \rangle \& \langle A!, y^P \rangle \& a \neq y$
 $\& (\lambda z . \langle R, a^P, z^P \rangle) = (\lambda z . \langle R, y^P, z^P \rangle) \text{ in } v]$
 using $\exists I$ **by** fast
 thus $[\exists x y . \langle A!, x^P \rangle \& \langle A!, y^P \rangle \& x \neq y$
 $\& (\lambda z . \langle R, x^P, z^P \rangle) = (\lambda z . \langle R, y^P, z^P \rangle) \text{ in } v]$
 using $\exists I$ **by** fast
 qed

lemma *aclassical-3*[PLM]:

$[\forall F . \exists x y . \langle A!, x^P \rangle \& \langle A!, y^P \rangle \& (x \neq y)$
 $\& ((\lambda^0 \langle F, x^P \rangle) = (\lambda^0 \langle F, y^P \rangle)) \text{ in } v]$
proof (rule $\forall I$)
 fix R
 obtain a where ϑ :
 $[\langle A!, a^P \rangle \& (\forall F . \langle a^P, F \rangle \equiv (\exists y . \langle A!, y^P \rangle$
 $\& F = (\lambda z . \langle R, y^P \rangle) \& \neg \langle y^P, F \rangle)) \text{ in } v]$
 using *A-objects*[*axiom-instance*] **by** (rule $\exists E$)
 {
 assume $[\neg \langle a^P, (\lambda z . \langle R, a^P \rangle) \rangle] \text{ in } v]$
 hence $[\neg(\langle A!, a^P \rangle \& (\lambda z . \langle R, a^P \rangle) = (\lambda z . \langle R, a^P \rangle))$

```

      &  $\neg \llbracket a^P, (\lambda z . \llbracket R, a^P \rrbracket) \rrbracket$  in  $v$ ]
    using  $\vartheta[\text{conj2}, \text{THEN } \forall E, \text{THEN oth-class-taut-5-d}[\text{equiv-lr}], \text{equiv-lr}]$ 
       $\text{cqt-further-4}[\text{equiv-lr}] \forall E$  by blast
  hence  $\llbracket \llbracket A!, a^P \rrbracket \ \& \ (\lambda z . \llbracket R, a^P \rrbracket) = (\lambda z . \llbracket R, a^P \rrbracket) \rrbracket$ 
     $\rightarrow \llbracket a^P, (\lambda z . \llbracket R, a^P \rrbracket) \rrbracket$  in  $v$ ]
    apply cut-tac by PLM-solver
  hence  $\llbracket \llbracket a^P, (\lambda z . \llbracket R, a^P \rrbracket) \rrbracket \rrbracket$  in  $v$ ]
    using  $\vartheta[\text{conj1}] \text{id-eq-1} \ \& I \text{vdash-properties-10}$  by fast
}
hence 1:  $\llbracket \llbracket a^P, (\lambda z . \llbracket R, a^P \rrbracket) \rrbracket \rrbracket$  in  $v$ ]
  using reductio-aa-1 CP if-p-then-p by blast
then obtain  $b$  where  $\xi$ :
 $\llbracket \llbracket A!, b^P \rrbracket \ \& \ (\lambda z . \llbracket R, a^P \rrbracket) = (\lambda z . \llbracket R, b^P \rrbracket) \rrbracket$ 
  &  $\neg \llbracket b^P, (\lambda z . \llbracket R, a^P \rrbracket) \rrbracket$  in  $v$ ]
  using  $\vartheta[\text{conj2}, \text{THEN } \forall E, \text{equiv-lr}] \exists E$  by blast
have  $[a \neq b \text{ in } v]$ 
  proof -
    {
      assume  $[a = b \text{ in } v]$ 
      hence  $\llbracket \llbracket b^P, (\lambda z . \llbracket R, a^P \rrbracket) \rrbracket \rrbracket$  in  $v$ ]
        using 1 l-identity[axiom-instance, deduction, deduction] by fast
      hence ?thesis
        using  $\xi[\text{conj2}] \text{reductio-aa-1}$  by blast
    }
    thus ?thesis using reductio-aa-1 by blast
  qed
moreover {
  have  $\llbracket \llbracket R, a^P \rrbracket = \llbracket R, b^P \rrbracket \rrbracket$  in  $v$ ]
    unfolding identityo-def
    using  $\xi[\text{conj1}, \text{conj2}]$  by auto
  hence  $\llbracket (\lambda^0 \llbracket R, a^P \rrbracket) = (\lambda^0 \llbracket R, b^P \rrbracket) \rrbracket$  in  $v$ ]
    using lambda-p-q-p-eq-q[equiv-rl] by simp
}
ultimately have  $\llbracket \llbracket A!, a^P \rrbracket \ \& \ \llbracket A!, b^P \rrbracket \ \& \ a \neq b \rrbracket$ 
  &  $\llbracket (\lambda^0 \llbracket R, a^P \rrbracket) = (\lambda^0 \llbracket R, b^P \rrbracket) \rrbracket$  in  $v$ ]
  using  $\vartheta[\text{conj1}] \ \xi[\text{conj1}, \text{conj1}] \ \xi[\text{conj1}, \text{conj2}] \ \& I$ 
  by presburger
hence  $\llbracket \exists y . \llbracket A!, a^P \rrbracket \ \& \ \llbracket A!, y^P \rrbracket \ \& \ a \neq y \rrbracket$ 
  &  $\llbracket (\lambda^0 \llbracket R, a^P \rrbracket) = (\lambda^0 \llbracket R, y^P \rrbracket) \rrbracket$  in  $v$ ]
  using  $\exists I$  by fast
thus  $\llbracket \exists x y . \llbracket A!, x^P \rrbracket \ \& \ \llbracket A!, y^P \rrbracket \ \& \ x \neq y \rrbracket$ 
  &  $\llbracket (\lambda^0 \llbracket R, x^P \rrbracket) = (\lambda^0 \llbracket R, y^P \rrbracket) \rrbracket$  in  $v$ ]
  using  $\exists I$  by fast
qed

```

lemma *aclassical2[PLM]*:

```

 $\llbracket \exists x y . \llbracket A!, x^P \rrbracket \ \& \ \llbracket A!, y^P \rrbracket \ \& \ x \neq y \ \& \ (\forall F . \llbracket F, x^P \rrbracket \equiv \llbracket F, y^P \rrbracket) \rrbracket$  in  $v$ ]
proof -
  let  $?R_1 = \lambda^2 (\lambda x y . \forall F . \llbracket F, x^P \rrbracket \equiv \llbracket F, y^P \rrbracket)$ 
  have  $\llbracket \exists x y . \llbracket A!, x^P \rrbracket \ \& \ \llbracket A!, y^P \rrbracket \ \& \ x \neq y \rrbracket$ 
    &  $\llbracket \lambda z . \llbracket ?R_1, z^P, x^P \rrbracket = (\lambda z . \llbracket ?R_1, z^P, y^P \rrbracket) \rrbracket$  in  $v$ ]
    using aclassical-1 by (rule  $\forall E$ )
  then obtain  $a$  where
     $\llbracket \exists y . \llbracket A!, a^P \rrbracket \ \& \ \llbracket A!, y^P \rrbracket \ \& \ a \neq y \rrbracket$ 
    &  $\llbracket \lambda z . \llbracket ?R_1, z^P, a^P \rrbracket = (\lambda z . \llbracket ?R_1, z^P, y^P \rrbracket) \rrbracket$  in  $v$ ]
    by (rule  $\exists E$ )
  then obtain  $b$  where ab-prop:
     $\llbracket \llbracket A!, a^P \rrbracket \ \& \ \llbracket A!, b^P \rrbracket \ \& \ a \neq b \rrbracket$ 
    &  $\llbracket \lambda z . \llbracket ?R_1, z^P, a^P \rrbracket = (\lambda z . \llbracket ?R_1, z^P, b^P \rrbracket) \rrbracket$  in  $v$ ]
    by (rule  $\exists E$ )
  have  $\llbracket \llbracket ?R_1, a^P, a^P \rrbracket \rrbracket$  in  $v$ ]
    apply (rule beta-C-meta-2[equiv-rl])
    apply (rule IsPropositional-intros)

```

```

    using oth-class-taut-4-a[THEN  $\forall I$ ] by fast
  hence  $[(\lambda z . (\lambda ?R_1, z^P, a^P), a^P)]$  in  $v$ 
    apply cut-tac apply (rule beta-C-meta-1[equiv-rl])
    apply (rule IsPropositional-intros)
  by auto
  hence  $[(\lambda z . (\lambda ?R_1, z^P, b^P), a^P)]$  in  $v$ 
    using ab-prop[conj2] l-identity[axiom-instance, deduction, deduction]
  by fast
  hence  $[(\lambda ?R_1, a^P, b^P)]$  in  $v$ 
    using beta-C-meta-1[equiv-lr] IsPropositional-intros by fast
  hence  $[\forall F. (F, a^P) \equiv (F, b^P)]$  in  $v$ 
    using beta-C-meta-2[equiv-lr] IsPropositional-intros by fast
  hence  $[(\lambda !, a^P) \& (\lambda !, b^P) \& a \neq b \& (\forall F. (F, a^P) \equiv (F, b^P))]$  in  $v$ 
    using ab-prop[conj1] &I by presburger
  hence  $[\exists y . (\lambda !, a^P) \& (\lambda !, y^P) \& a \neq y \& (\forall F. (F, a^P) \equiv (F, y^P))]$  in  $v$ 
    using  $\exists I$  by fast
  thus ?thesis using  $\exists I$  by fast
qed

```

9.13 Propositional Properties

lemma prop-prop2-1:

```

 $[\forall p . \exists F . F = (\lambda x . p)]$  in  $v$ 
proof (rule  $\forall I$ )
  fix p
  have  $[(\lambda x . p) = (\lambda x . p)]$  in  $v$ 
    using id-eq-prop-prop-1 by auto
  thus  $[\exists F . F = (\lambda x . p)]$  in  $v$ 
    by PLM-solver
qed

```

lemma prop-prop2-2:

```

 $[F = (\lambda x . p) \rightarrow \Box(\forall x . (F, x^P) \equiv p)]$  in  $v$ 
proof (rule CP)
  assume 1:  $[F = (\lambda x . p)]$  in  $v$ 
  {
    fix v
    {
      fix x
      have  $[(\lambda x . p), x^P] \equiv p$  in  $v$ 
        apply (rule beta-C-meta-1)
        by (rule IsPropositional-intros)+
    }
    hence  $[\forall x . (\lambda x . p), x^P] \equiv p$  in  $v$ 
      by (rule  $\forall I$ )
  }
  hence  $[\Box(\forall x . (\lambda x . p), x^P) \equiv p]$  in  $v$ 
    by (rule RN)
  thus  $[\Box(\forall x . (F, x^P) \equiv p)]$  in  $v$ 
    using l-identity[axiom-instance, deduction, deduction,
      OF 1[THEN id-eq-prop-prop-2[deduction]]] by fast
qed

```

lemma prop-prop2-3:

```

 $[Propositional F \rightarrow \Box(Propositional F)]$  in  $v$ 
proof (rule CP)
  assume  $[Propositional F]$  in  $v$ 
  hence  $[\exists p . F = (\lambda x . p)]$  in  $v$ 
    unfolding Propositional-def .
  then obtain q where  $[F = (\lambda x . q)]$  in  $v$ 
    by (rule  $\exists E$ )
  hence  $[\Box(F = (\lambda x . q))]$  in  $v$ 
    using id-nec[equiv-lr] by auto

```

```

hence  $[\exists p . \Box(F = (\lambda x . p)) \text{ in } v]$ 
  using  $\exists I$  by fast
thus  $[\Box(\text{Propositional } F) \text{ in } v]$ 
  unfolding Propositional-def
  using sign-S5-thm-1[deduction] by fast
qed

```

lemma *prop-indis*:

```

 $[\text{Indiscriminate } F \rightarrow (\neg(\exists x y . \langle F, x^P \rangle \ \& \ \neg\langle F, y^P \rangle)) \text{ in } v]$ 
proof (rule CP)
  assume  $[\text{Indiscriminate } F \text{ in } v]$ 
  hence 1:  $[\Box((\exists x . \langle F, x^P \rangle) \rightarrow (\forall x . \langle F, x^P \rangle)) \text{ in } v]$ 
    unfolding Indiscriminate-def .
  {
    assume  $[\exists x y . \langle F, x^P \rangle \ \& \ \neg\langle F, y^P \rangle \text{ in } v]$ 
    then obtain  $x$  where  $[\exists y . \langle F, x^P \rangle \ \& \ \neg\langle F, y^P \rangle \text{ in } v]$ 
      by (rule  $\exists E$ )
    then obtain  $y$  where 2:  $[\langle F, x^P \rangle \ \& \ \neg\langle F, y^P \rangle \text{ in } v]$ 
      by (rule  $\exists E$ )
    hence  $[\exists x . \langle F, x^P \rangle \text{ in } v]$ 
      using  $\&E(1) \ \exists I$  by fast
    hence  $[\forall x . \langle F, x^P \rangle \text{ in } v]$ 
      using 1[THEN qml-2[axiom-instance, deduction], deduction] by fast
    hence  $[\langle F, y^P \rangle \text{ in } v]$ 
      using cqt-orig-1[deduction] by fast
    hence  $[\langle F, y^P \rangle \ \& \ \neg\langle F, y^P \rangle \text{ in } v]$ 
      using 2  $\&I \ \&E$  by fast
    hence  $[\neg(\exists x y . \langle F, x^P \rangle \ \& \ \neg\langle F, y^P \rangle) \text{ in } v]$ 
      using pl-1[axiom-instance, deduction, THEN modus-tollens-1]
      oth-class-taut-1-a by blast
  }
  thus  $[\neg(\exists x y . \langle F, x^P \rangle \ \& \ \neg\langle F, y^P \rangle) \text{ in } v]$ 
    using reductio-aa-2 if-p-then-p deduction-theorem by blast
qed

```

lemma *prop-in-thm*:

```

 $[\text{Propositional } F \rightarrow \text{Indiscriminate } F \text{ in } v]$ 
proof (rule CP)
  assume  $[\text{Propositional } F \text{ in } v]$ 
  hence  $[\Box(\text{Propositional } F) \text{ in } v]$ 
    using prop-prop2-3[deduction] by auto
  moreover {
    fix  $w$ 
    assume  $[\exists p . (F = (\lambda y . p)) \text{ in } w]$ 
    then obtain  $q$  where q-prop:  $[F = (\lambda y . q) \text{ in } w]$ 
      by (rule  $\exists E$ )
    {
      assume  $[\exists x . \langle F, x^P \rangle \text{ in } w]$ 
      then obtain  $a$  where  $[\langle F, a^P \rangle \text{ in } w]$ 
        by (rule  $\exists E$ )
      hence  $[\langle \lambda y . q, a^P \rangle \text{ in } w]$ 
        using q-prop l-identity[axiom-instance, deduction, deduction] by fast
      hence  $q$ :  $[q \text{ in } w]$ 
        using beta-C-meta-1[equiv-lr] IsPropositional-intros by fast
    }
    fix  $x$ 
    have  $[\langle \lambda y . q, x^P \rangle \text{ in } w]$ 
      using q beta-C-meta-1[equiv-rl] IsPropositional-intros by fast
    hence  $[\langle F, x^P \rangle \text{ in } w]$ 
      using q-prop[eq-sym] l-identity[axiom-instance, deduction, deduction]
      by fast
  }

```

```

    }
    hence  $[\forall x . \langle F, x^P \rangle \text{ in } w]$ 
      by (rule  $\forall I$ )
  }
  hence  $[(\exists x . \langle F, x^P \rangle) \rightarrow (\forall x . \langle F, x^P \rangle) \text{ in } w]$ 
    by (rule  $CP$ )
}
ultimately show  $[Indiscriminate\ F \text{ in } v]$ 
  unfolding Propositional-def Indiscriminate-def
  using RM-1[deduction] deduction-theorem by blast
qed

```

lemma *prop-in-f-1*:
 $[Necessary\ F \rightarrow Indiscriminate\ F \text{ in } v]$
 unfolding *Necessary-defs Indiscriminate-def*
 using *pl-1[axiom-instance, THEN RM-1]* by simp

lemma *prop-in-f-2*:
 $[Impossible\ F \rightarrow Indiscriminate\ F \text{ in } v]$
proof –
 {
 fix w
 have $[(\neg(\exists x . \langle F, x^P \rangle)) \rightarrow ((\exists x . \langle F, x^P \rangle) \rightarrow (\forall x . \langle F, x^P \rangle)) \text{ in } w]$
 using *useful-tautologies-3* by auto
 hence $[(\forall x . \neg\langle F, x^P \rangle) \rightarrow ((\exists x . \langle F, x^P \rangle) \rightarrow (\forall x . \langle F, x^P \rangle)) \text{ in } w]$
 apply *cut-tac* apply (*PLM-subst-method* $\neg(\exists x . \langle F, x^P \rangle) (\forall x . \neg\langle F, x^P \rangle)$)
 using *cqt-further-4* unfolding *exists-def* by fast+
 }
 thus ?thesis
 unfolding *Impossible-defs Indiscriminate-def* using *RM-1 CP* by blast
qed

lemma *prop-in-f-3-a*:
 $[\neg(Indiscriminate\ (E!)) \text{ in } v]$
proof (rule *reductio-aa-2*)
 show $[\Box\neg(\forall x . \langle E!, x^P \rangle) \text{ in } v]$
 using *a-objects-exist-3* .
 next
 assume $[Indiscriminate\ E! \text{ in } v]$
 thus $[\neg\Box\neg(\forall x . \langle E!, x^P \rangle) \text{ in } v]$
 unfolding *Indiscriminate-def*
 using *o-objects-exist-1 KBasic2-5[deduction,deduction]*
 unfolding *diamond-def* by blast
qed

lemma *prop-in-f-3-b*:
 $[\neg(Indiscriminate\ (E!^\neg)) \text{ in } v]$
proof (rule *reductio-aa-2*)
 assume $[Indiscriminate\ (E!^\neg) \text{ in } v]$
 moreover have $[\Box(\exists x . \langle E!^\neg, x^P \rangle) \text{ in } v]$
 apply (*PLM-subst1-method* $\lambda x . \neg\langle E!, x^P \rangle \lambda x . \langle E!^\neg, x^P \rangle$)
 using *thm-relation-negation-1-1[equiv-sym]* apply simp
 unfolding *exists-def*
 apply (*PLM-subst1-method* $\lambda x . \langle E!, x^P \rangle \lambda x . \neg\neg\langle E!, x^P \rangle$)
 using *oth-class-taut-4-b* apply simp
 using *a-objects-exist-3* by auto
 ultimately have $[\Box(\forall x . \langle E!^\neg, x^P \rangle) \text{ in } v]$
 unfolding *Indiscriminate-def*
 using *qml-1[axiom-instance, deduction, deduction]* by blast
 thus $[\Box(\forall x . \neg\langle E!, x^P \rangle) \text{ in } v]$
 apply *cut-tac*
 apply (*PLM-subst1-method* $\lambda x . \langle E!^\neg, x^P \rangle \lambda x . \neg\langle E!, x^P \rangle$)
 using *thm-relation-negation-1-1* by auto

```

next
show  $[\neg \Box (\forall x . \neg (E!, x^P)) \text{ in } v]$ 
  using o-objects-exist-1
  unfolding diamond-def exists-def
  apply cut-tac
  apply (PLM-subst-method  $\neg \neg (\forall x . \neg (E!, x^P)) \forall x . \neg (E!, x^P)$ )
  using oth-class-taut-4-b[equiv-sym] by auto
qed

lemma prop-in-f-3-c:
 $[\neg (\text{Indiscriminate } (O!)) \text{ in } v]$ 
proof (rule reductio-aa-2)
  show  $[\neg (\forall x . (O!, x^P)) \text{ in } v]$ 
    using a-objects-exist-2 [THEN qml-2[axiom-instance, deduction]]
    by blast
next
  assume [Indiscriminate O! in v]
  thus  $[(\forall x . (O!, x^P)) \text{ in } v]$ 
    unfolding Indiscriminate-def
    using o-objects-exist-2 qml-1[axiom-instance, deduction, deduction]
    qml-2[axiom-instance, deduction] by blast
qed

lemma prop-in-f-3-d:
 $[\neg (\text{Indiscriminate } (A!)) \text{ in } v]$ 
proof (rule reductio-aa-2)
  show  $[\neg (\forall x . (A!, x^P)) \text{ in } v]$ 
    using o-objects-exist-3 [THEN qml-2[axiom-instance, deduction]]
    by blast
next
  assume [Indiscriminate A! in v]
  thus  $[(\forall x . (A!, x^P)) \text{ in } v]$ 
    unfolding Indiscriminate-def
    using a-objects-exist-1 qml-1[axiom-instance, deduction, deduction]
    qml-2[axiom-instance, deduction] by blast
qed

lemma prop-in-f-4-a:
 $[\neg (\text{Propositional } E!) \text{ in } v]$ 
  using prop-in-thm[deduction] prop-in-f-3-a modus-tollens-1 CP
  by meson

lemma prop-in-f-4-b:
 $[\neg (\text{Propositional } (E!^-)) \text{ in } v]$ 
  using prop-in-thm[deduction] prop-in-f-3-b modus-tollens-1 CP
  by meson

lemma prop-in-f-4-c:
 $[\neg (\text{Propositional } (O!)) \text{ in } v]$ 
  using prop-in-thm[deduction] prop-in-f-3-c modus-tollens-1 CP
  by meson

lemma prop-in-f-4-d:
 $[\neg (\text{Propositional } (A!)) \text{ in } v]$ 
  using prop-in-thm[deduction] prop-in-f-3-d modus-tollens-1 CP
  by meson

lemma prop-prop-nec-1:
 $[\Diamond (\exists p . F = (\lambda x . p)) \rightarrow (\exists p . F = (\lambda x . p)) \text{ in } v]$ 
proof (rule CP)
  assume  $[\Diamond (\exists p . F = (\lambda x . p)) \text{ in } v]$ 
  hence  $[\exists p . \Diamond (F = (\lambda x . p)) \text{ in } v]$ 
    using BF $\Diamond$ [deduction] by auto

```

then obtain p where $[\Diamond(F = (\lambda x . p)) \text{ in } v]$
by (*rule $\exists E$*)
hence $[\Box(\forall x. \llbracket x^P, F \rrbracket \equiv \llbracket x^P, \lambda x. p \rrbracket) \text{ in } v]$
unfolding *identity-defs* .
hence $[\Box(\forall x. \llbracket x^P, F \rrbracket \equiv \llbracket x^P, \lambda x. p \rrbracket) \text{ in } v]$
using $5\Diamond[\text{deduction}]$ **by** *auto*
hence $[(F = (\lambda x . p)) \text{ in } v]$
unfolding *identity-defs* .
thus $[\exists p . (F = (\lambda x . p)) \text{ in } v]$
by *PLM-solver*
qed

lemma *prop-prop-nec-2*:

$[(\forall p . F \neq (\lambda x . p)) \rightarrow \Box(\forall p . F \neq (\lambda x . p)) \text{ in } v]$
apply (*PLM-subst-method*
 $\neg(\exists p . (F = (\lambda x . p)))$
 $(\forall p . \neg(F = (\lambda x . p))))$
using *cqt-further-4* **apply** *blast*
apply (*PLM-subst-method*
 $\neg\Diamond(\exists p . F = (\lambda x . p))$
 $\Box\neg(\exists p . F = (\lambda x . p)))$
using *KBasic2-4[equiv-sym]* *prop-prop-nec-1*
contraposition-1 **by** *auto*

lemma *prop-prop-nec-3*:

$[(\exists p . F = (\lambda x . p)) \rightarrow \Box(\exists p . F = (\lambda x . p)) \text{ in } v]$
using *prop-prop-nec-1* *derived-S5-rules-1-b* **by** *simp*

lemma *prop-prop-nec-4*:

$[\Diamond(\forall p . F \neq (\lambda x . p)) \rightarrow (\forall p . F \neq (\lambda x . p)) \text{ in } v]$
using *prop-prop-nec-2* *derived-S5-rules-2-b* **by** *simp*

lemma *enc-prop-nec-1*:

$[\Diamond(\forall F . \llbracket x^P, F \rrbracket \rightarrow (\exists p . F = (\lambda x . p)))$
 $\rightarrow (\forall F . \llbracket x^P, F \rrbracket \rightarrow (\exists p . F = (\lambda x . p))) \text{ in } v]$
proof (*rule CP*)
assume $[\Diamond(\forall F . \llbracket x^P, F \rrbracket \rightarrow (\exists p . F = (\lambda x . p))) \text{ in } v]$
hence $1: [(\forall F . \Diamond(\llbracket x^P, F \rrbracket \rightarrow (\exists p . F = (\lambda x . p)))) \text{ in } v]$
using *BuridanDiamond[deduction]* **by** *auto*
{
fix Q
assume $[\llbracket x^P, Q \rrbracket \text{ in } v]$
hence $[\Box\llbracket x^P, Q \rrbracket \text{ in } v]$
using *encoding[axiom-instance, deduction]* **by** *auto*
moreover have $[\Diamond(\llbracket x^P, Q \rrbracket \rightarrow (\exists p . Q = (\lambda x . p))) \text{ in } v]$
using *cqt-1[axiom-instance, deduction]* 1 **by** *auto*
ultimately have $[\Diamond(\exists p . Q = (\lambda x . p)) \text{ in } v]$
using *KBasic2-9[equiv-lr, deduction]* **by** *auto*
hence $[(\exists p . Q = (\lambda x . p)) \text{ in } v]$
using *prop-prop-nec-1[deduction]* **by** *auto*
}
thus $[(\forall F . \llbracket x^P, F \rrbracket \rightarrow (\exists p . F = (\lambda x . p))) \text{ in } v]$
apply *cut-tac* **by** *PLM-solver*
qed

lemma *enc-prop-nec-2*:

$[(\forall F . \llbracket x^P, F \rrbracket \rightarrow (\exists p . F = (\lambda x . p))) \rightarrow \Box(\forall F . \llbracket x^P, F \rrbracket$
 $\rightarrow (\exists p . F = (\lambda x . p))) \text{ in } v]$
using *derived-S5-rules-1-b* *enc-prop-nec-1* **by** *blast*

end
end

10 Possible Worlds

locale *PossibleWorlds* = *PLM*
begin

10.1 Definitions

definition *Situation* **where**

Situation $x \equiv \langle A!, x \rangle \ \& \ (\forall F. \llbracket x, F \rrbracket \rightarrow \text{Propositional } F)$

definition *EncodeProposition* (infixl Σ 70) **where**

$x \Sigma p \equiv \langle A!, x \rangle \ \& \ \llbracket x, \lambda x. p \rrbracket$

definition *TrueInSituation* (infixl \models 10) **where**

$x \models p \equiv \text{Situation } x \ \& \ x \Sigma p$

definition *PossibleWorld* **where**

PossibleWorld $x \equiv \text{Situation } x \ \& \ \Diamond (\forall p. x \Sigma p \equiv p)$

10.2 Auxiliary Lemmata

lemma *possit-sit-1*:

$[\text{Situation } (x^P) \equiv \Box(\text{Situation } (x^P)) \text{ in } v]$

proof (rule $\equiv I$; rule *CP*)

assume $[\text{Situation } (x^P) \text{ in } v]$

hence 1: $[\langle A!, x^P \rangle \ \& \ (\forall F. \llbracket x^P, F \rrbracket \rightarrow \text{Propositional } F) \text{ in } v]$

unfolding *Situation-def* **by** *auto*

have $[\Box \langle A!, x^P \rangle \text{ in } v]$

using 1[*conj1*, *THEN oa-facts-2[deduction]*].

moreover have $[\Box(\forall F. \llbracket x^P, F \rrbracket \rightarrow \text{Propositional } F) \text{ in } v]$

using 1[*conj2*] unfolding *Propositional-def*

by (rule *enc-prop-nec-2[deduction]*)

ultimately show $[\Box \text{Situation } (x^P) \text{ in } v]$

unfolding *Situation-def*

apply *cut-tac* **apply** (rule *KBasic-3[equiv-rl]*)

by (rule *intro-elim-1*)

next

assume $[\Box \text{Situation } (x^P) \text{ in } v]$

thus $[\text{Situation } (x^P) \text{ in } v]$

using *qml-2[axiom-instance, deduction]* **by** *auto*

qed

lemma *possworld-nec*:

$[\text{PossibleWorld } (x^P) \equiv \Box(\text{PossibleWorld } (x^P)) \text{ in } v]$

apply (rule $\equiv I$; rule *CP*)

subgoal unfolding *PossibleWorld-def*

apply (rule *KBasic-3[equiv-rl]*)

apply (rule *intro-elim-1*)

using *possit-sit-1[equiv-lr]* $\& E(1)$ **apply** *blast*

using *qml-3[axiom-instance, deduction]* $\& E(2)$ **by** *blast*

using *qml-2[axiom-instance, deduction]* **by** *auto*

lemma *TrueInWorldNec*:

$[\Box(x^P \models p) \equiv \Box(\Box(x^P \models p)) \text{ in } v]$

proof (rule $\equiv I$; rule *CP*)

assume $[x^P \models p \text{ in } v]$

hence $[\text{Situation } (x^P) \ \& \ (\langle A!, x^P \rangle \ \& \ \llbracket x^P, \lambda x. p \rrbracket) \text{ in } v]$

unfolding *TrueInSituation-def* *EncodeProposition-def*.

hence $[(\Box \text{Situation } (x^P) \ \& \ \Box \langle A!, x^P \rangle) \ \& \ \Box \llbracket x^P, \lambda x. p \rrbracket \text{ in } v]$

using $\& I$ $\& E$ *possit-sit-1[equiv-lr]* *oa-facts-2[deduction]*

encoding[axiom-instance, deduction] **by** *metis*

thus $[\Box(\Box(x^P \models p)) \text{ in } v]$

unfolding *TrueInSituation-def* *EncodeProposition-def*

using *KBasic-3[equiv-rl]* $\& I$ $\& E$ **by** *metis*

next

assume $[\Box(x^P \models p) \text{ in } v]$

thus $[x^P \models p \text{ in } v]$
 using *qml-2[axiom-instance,deduction]* by *auto*
 qed

lemma *PossWorldAux*:

$[(\langle A!, x^P \rangle \ \& \ (\forall F . (\langle x^P, F \rangle \equiv (\exists p . p \ \& \ (F = (\lambda x . p)))))) \rightarrow (\text{PossibleWorld } (x^P)) \text{ in } v]$

proof (*rule CP*)

assume *DefX*: $[(\langle A!, x^P \rangle \ \& \ (\forall F . (\langle x^P, F \rangle \equiv (\exists p . p \ \& \ (F = (\lambda x . p)))))) \text{ in } v]$

have [*Situation* (x^P) in v]

proof –

have $[(\langle A!, x^P \rangle) \text{ in } v]$

using *DefX[conj1]* .

moreover have $[(\forall F . \langle x^P, F \rangle \rightarrow \text{Propositional } F) \text{ in } v]$

proof (*rule* $\forall I$; *rule CP*)

fix F

assume $[\langle x^P, F \rangle \text{ in } v]$

moreover have $[\langle x^P, F \rangle \equiv (\exists p . p \ \& \ (F = (\lambda x . p))) \text{ in } v]$

using *DefX[conj2]* *cqt-1[axiom-instance, deduction]* by *auto*

ultimately have $[(\exists p . p \ \& \ (F = (\lambda x . p))) \text{ in } v]$

using $\equiv E(1)$ by *blast*

then obtain p where $[p \ \& \ (F = (\lambda x . p)) \text{ in } v]$

by (*rule* $\exists E$)

hence $[(F = (\lambda x . p)) \text{ in } v]$

by (*rule* $\&E(2)$)

hence $[(\exists p . (F = (\lambda x . p))) \text{ in } v]$

by *PLM-solver*

thus [*Propositional* F in v]

unfolding *Propositional-def* .

qed

ultimately show [*Situation* (x^P) in v]

unfolding *Situation-def* by (*rule* $\&I$)

qed

moreover have $[\Diamond(\forall p . x^P \ \Sigma p \equiv p) \text{ in } v]$

unfolding *EncodeProposition-def*

proof (*rule* *TBasic[deduction]*; *rule* $\forall I$)

fix q

have *EncodeLambda*:

$[\langle x^P, \lambda x . q \rangle \equiv (\exists p . p \ \& \ ((\lambda x . q) = (\lambda x . p))) \text{ in } v]$

using *DefX[conj2]* by (*rule cqt-1[axiom-instance, deduction]*)

moreover {

assume $[q \text{ in } v]$

moreover have $[(\lambda x . q) = (\lambda x . q) \text{ in } v]$

using *id-eq-prop-prop-1* by *auto*

ultimately have $[q \ \& \ ((\lambda x . q) = (\lambda x . q)) \text{ in } v]$

by (*rule* $\&I$)

hence $[\exists p . p \ \& \ ((\lambda x . q) = (\lambda x . p)) \text{ in } v]$

by *PLM-solver*

moreover have $[(\langle A!, x^P \rangle) \text{ in } v]$

using *DefX[conj1]* .

ultimately have $[(\langle A!, x^P \rangle \ \& \ \langle x^P, \lambda x . q \rangle) \text{ in } v]$

using *EncodeLambda[equiv-rl]* $\&I$ by *auto*

}

moreover {

assume $[(\langle A!, x^P \rangle \ \& \ \langle x^P, \lambda x . q \rangle) \text{ in } v]$

hence $[\langle x^P, \lambda x . q \rangle \text{ in } v]$

using $\&E(2)$ by *auto*

hence $[\exists p . p \ \& \ ((\lambda x . q) = (\lambda x . p)) \text{ in } v]$

using *EncodeLambda[equiv-lr]* by *auto*

then obtain p where *p-and-lambda-q-is-lambda-p*:

```

    [p & ((λx. q) = (λ x . p)) in v]
  by (rule ∃ E)
have [(λ x . p), xP] ≡ p in v]
  apply (rule beta-C-meta-1)
  by (rule IsPropositional-intros)+
hence [(λ x . p), xP] in v]
  using p-and-lambda-q-is-lambda-p[conj1] ≡E(2) by auto
hence [(λ x . q), xP] in v]
  using p-and-lambda-q-is-lambda-p[conj2, THEN id-eq-prop-prop-2[deduction]]
  l-identity[axiom-instance, deduction, deduction] by fast
moreover have [(λ x . q), xP] ≡ q in v]
  apply (rule beta-C-meta-1) by (rule IsPropositional-intros)+
ultimately have [q in v]
  using ≡E(1) by blast
}
ultimately show [(λ A!, xP) & (λ xP, λ x. q)] ≡ q in v]
  using &I ≡I CP by auto
qed

ultimately show [PossibleWorld (xP) in v]
  unfolding PossibleWorld-def by (rule &I)
qed

```

10.3 For every syntactic Possible World there is a semantic Possible World

theorem *SemanticPossibleWorldForSyntacticPossibleWorlds:*

$\forall x . [PossibleWorld (x^P) in w] \longrightarrow$
 $(\exists v . \forall p . [p in v] \longleftrightarrow [(x^P \models p) in w])$

proof

```

fix x
{
  assume PossWorldX: [PossibleWorld (xP) in w]
  hence SituationX: [Situation (xP) in w]
    unfolding PossibleWorld-def apply cut-tac by PLM-solver
  have PossWorldExpanded:
    [(λ A!, xP) & (∀ F. (λ xP, F] → (∃ p. F = (λ x. p)))]
    & (∃ p. (λ A!, xP) & (λ xP, λ x. p] ≡ p) in w]
    using PossWorldX
    unfolding PossibleWorld-def Situation-def
      Propositional-def EncodeProposition-def .
  have AbstractX: [(λ A!, xP) in w]
    using PossWorldExpanded[conj1, conj1] .

  have [(λ p. (λ xP, λ x. p] ≡ p) in w]
    apply (PLM-subst1-method
      λ p. (λ A!, xP) & (λ xP, λ x. p]
      λ p . (λ xP, λ x. p])
    subgoal using PossWorldExpanded[conj1, conj1, THEN oa-facts-2[deduction]]
      using Semantics.T6 apply cut-tac by PLM-solver
    using PossWorldExpanded[conj2] .

  hence ∃ v. ∀ p. ((λ xP, λ x. p] in v))
    = [p in v]
    unfolding diamond-def equiv-def conj-def
    apply (simp add: Semantics.T4 Semantics.T6 Semantics.T5
      Semantics.T8)

  by auto

  then obtain v where PropsTrueInSemWorld:
    ∀ p. ((λ xP, λ x. p] in v) = [p in v]
    by auto
}

```

```

fix p
{
  assume  $[(x^P) \models p] \text{ in } w$ 
  hence  $[(x^P) \models p] \text{ in } v$ 
    using TrueInWorldNec[equiv-lr] Semantics.T6 by simp
  hence  $[Situation(x^P) \ \& \ (\lambda A!.x^P) \ \& \ \lambda x. p] \text{ in } v$ 
    unfolding TrueInSituation-def EncodeProposition-def .
  hence  $[\lambda x^P. \lambda x. p] \text{ in } v$ 
    using  $\&E(2)$  by blast
  hence  $[p \text{ in } v]$ 
    using PropsTrueInSemWorld by blast
}
moreover {
  assume  $[p \text{ in } v]$ 
  hence  $[\lambda x^P. \lambda x. p] \text{ in } v$ 
    using PropsTrueInSemWorld by blast
  hence  $[(x^P) \models p \text{ in } v]$ 
    apply cut-tac unfolding TrueInSituation-def EncodeProposition-def
    apply (rule  $\&I$ ) using SituationX[THEN possit-sit-1[equiv-lr]]
    subgoal using Semantics.T6 by auto
    apply (rule  $\&I$ )
    subgoal using AbstractX[THEN oa-facts-2[deduction]]
      using Semantics.T6 by auto
    by assumption
  hence  $[\Box((x^P) \models p) \text{ in } v]$ 
    using TrueInWorldNec[equiv-lr] by simp
  hence  $[(x^P) \models p \text{ in } w]$ 
    using Semantics.T6 by simp
}
ultimately have  $[p \text{ in } v] \longleftrightarrow [(x^P) \models p \text{ in } w]$ 
  by auto
}
hence  $(\exists v . \forall p . [p \text{ in } v] \longleftrightarrow [(x^P) \models p \text{ in } w])$ 
  by blast
}
thus  $[PossibleWorld(x^P) \text{ in } w] \longrightarrow$ 
   $(\exists v . \forall p . [p \text{ in } v] \longleftrightarrow [(x^P) \models p \text{ in } w])$ 
  by blast
qed

```

10.4 For every semantic Possible World there is a syntactic Possible World

theorem *SyntacticPossibleWorldForSemanticPossibleWorlds*:

$\forall v . \exists x . [PossibleWorld(x^P) \text{ in } w] \wedge$
 $(\forall p . [p \text{ in } v] \longleftrightarrow [((x^P) \models p) \text{ in } w])$

proof

```

fix v
have  $[\exists x. (\lambda A!.x^P) \ \& \ (\forall F . (\lambda x^P. F] \equiv$ 
   $(\exists p . p \ \& \ (F = (\lambda x . p)))) \text{ in } v]$ 
  using A-objects[axiom-instance] by fast
then obtain x where DefX:
 $[(\lambda A!.x^P) \ \& \ (\forall F . (\lambda x^P. F] \equiv (\exists p . p \ \& \ (F = (\lambda x . p)))) \text{ in } v]$ 
  by (rule  $\exists E$ )
hence PossWorldX:  $[PossibleWorld(x^P) \text{ in } v]$ 
  using PossWorldAux[deduction] by blast
hence  $[PossibleWorld(x^P) \text{ in } w]$ 
  using possworld-nec[equiv-lr] Semantics.T6 by auto
moreover have  $(\forall p . [p \text{ in } v] \longleftrightarrow [(x^P) \models p \text{ in } w])$ 
proof
  fix q
  {
    assume  $[q \text{ in } v]$ 

```

```

    moreover have  $[(\lambda x . q) = (\lambda x . q) \text{ in } v]$ 
      using id-eq-prop-prop-1 by auto
    ultimately have  $[q \ \& \ (\lambda x . q) = (\lambda x . q) \text{ in } v]$ 
      using &I by auto
    hence  $[(\exists p . p \ \& \ ((\lambda x . q) = (\lambda x . p))) \text{ in } v]$ 
      by PLM-solver
    hence  $\lambda: [\![x^P, (\lambda x . q)]\!] \text{ in } v$ 
      using cqt-1[axiom-instance, deduction, OF DefX[conj2], equiv-rl]
      by blast
    have  $[(x^P \models q) \text{ in } v]$ 
      unfolding TrueInSituation-def apply (rule &I)
      using PossWorldX unfolding PossibleWorld-def
      using &E(1) apply blast
      unfolding EncodeProposition-def apply (rule &I)
      using DefX[conj1] apply simp
      using  $\lambda$  .
    hence  $[(x^P \models q) \text{ in } w]$ 
      using TrueInWorldNecc[equiv-lr] Semantics.T6 by auto
  }
  moreover {
    assume  $[(x^P \models q) \text{ in } w]$ 
    hence  $[(x^P \models q) \text{ in } v]$ 
      using TrueInWorldNecc[equiv-lr] Semantics.T6
      by auto
    hence  $[\![x^P, (\lambda x . q)]\!] \text{ in } v$ 
      unfolding TrueInSituation-def EncodeProposition-def
      using &E(2) by blast
    hence  $[(\exists p . p \ \& \ ((\lambda x . q) = (\lambda x . p))) \text{ in } v]$ 
      using cqt-1[axiom-instance, deduction, OF DefX[conj2], equiv-lr]
      by blast
    then obtain  $p$  where  $\lambda$ :
       $[(p \ \& \ ((\lambda x . q) = (\lambda x . p))) \text{ in } v]$ 
      by (rule  $\exists E$ )
    have  $[\![ (\lambda x . p), x^P ]\!] \equiv p \text{ in } v$  apply (rule beta-C-meta-1)
      by (rule IsPropositional-intros) +
    hence  $[\![ (\lambda x . q), x^P ]\!] \equiv p \text{ in } v$ 
      using l-identity[where  $\beta = (\lambda x . q)$  and  $\alpha = (\lambda x . p)$ ,
axiom-instance, deduction, deduction]
      using  $\lambda$ [conj2, THEN id-eq-prop-prop-2[deduction]] by meson
    hence  $[\![ (\lambda x . q), x^P ]\!] \text{ in } v$  using  $\lambda$ [conj1]  $\equiv E(2)$  by blast
    moreover have  $[\![ (\lambda x . q), x^P ]\!] \equiv q \text{ in } v$ 
      apply (rule beta-C-meta-1)
      by (rule IsPropositional-intros) +
    ultimately have  $[q \text{ in } v]$ 
      using  $\equiv E(1)$  by blast
  }
  ultimately show  $[q \text{ in } v] \longleftrightarrow [(x^P \models q) \text{ in } w]$ 
    by blast
qed
ultimately show  $\exists x . [PossibleWorld (x^P) \text{ in } w]$ 
   $\wedge (\forall p . [p \text{ in } v] \longleftrightarrow [(x^P \models p) \text{ in } w])$ 
  by auto
qed
end

```

11 Sanity Tests

```

locale SanityTests
begin
  interpretation MetaSolver.
  interpretation Semantics.

```

11.1 Consistency

```
lemma True
  nitpick[expect=genuine, user-axioms, satisfy]
  by auto
```

11.2 Intensionality

```
lemma [(\lambda y. (q \vee \neg q)) = (\lambda y. (p \vee \neg p)) in v]
  unfolding identity-\Pi_1-def
  apply (rule Eq_1I) apply (simp add: meta-defs)
  nitpick[expect = genuine, user-axioms=true,
    sat-solver = MiniSat-JNI,
    card i = 2, card j = 2, card \sigma = 1, card \omega = 1,
    card (i \Rightarrow bool) \times i = 4,
    card (i \Rightarrow bool) \times (i \Rightarrow bool) \times i = 4,
    card v = 2, verbose, show-all, debug]
oops — Countermodel by Nitpick

lemma [(\lambda y. (p \vee q)) = (\lambda y. (q \vee p)) in v]
  unfolding identity-\Pi_1-def
  apply (rule Eq_1I) apply (simp add: meta-defs)
  nitpick[expect = genuine, user-axioms=true,
    sat-solver = MiniSat-JNI,
    card i = 2, card j = 2, card \sigma = 1,
    card \omega = 1, card (i \Rightarrow bool) \times i = 4,
    card (i \Rightarrow bool) \times (i \Rightarrow bool) \times i = 4,
    card v = 2, verbose, show-all, debug]
oops — Countermodel by Nitpick
```

11.3 Concreteness coindices with Object Domains

```
lemma OrdCheck:
  [(\lambda x . \neg \Box(\neg(E!, x^P)), x) in v] \longleftrightarrow
  (denotes x) \wedge (case (denotation x) of \omega\nu y \Rightarrow True | - \Rightarrow False)
  using OrdinaryObjectsPossiblyConcreteAxiom
  by (simp add: meta-defs meta-aux split: \nu.split v.split)

lemma AbsCheck:
  [(\lambda x . \Box(\neg(E!, x^P)), x) in v] \longleftrightarrow
  (denotes x) \wedge (case (denotation x) of \alpha\nu y \Rightarrow True | - \Rightarrow False)
  using OrdinaryObjectsPossiblyConcreteAxiom
  by (simp add: meta-defs meta-aux split: \nu.split v.split)
```

11.4 Justification for Meta-Logical Axioms

Remark 24. *OrdinaryObjectsPossiblyConcreteAxiom is equivalent to "all ordinary objects are possibly concrete".*

```
lemma OrdAxiomCheck:
  OrdinaryObjectsPossiblyConcrete \longleftrightarrow
  (\forall x. ((\lambda x . \neg \Box(\neg(E!, x^P)), x^P) in v)
    \longleftrightarrow (case x of \omega\nu y \Rightarrow True | - \Rightarrow False)))
  unfolding Concrete-def by (auto simp: meta-defs meta-aux split: \nu.split v.split)
```

Remark 25. *OrdinaryObjectsPossiblyConcreteAxiom is equivalent to "all abstract objects are necessarily not concrete".*

```
lemma AbsAxiomCheck:
  OrdinaryObjectsPossiblyConcrete \longleftrightarrow
  (\forall x. ((\lambda x . \Box(\neg(E!, x^P)), x^P) in v)
    \longleftrightarrow (case x of \alpha\nu y \Rightarrow True | - \Rightarrow False)))
  by (auto simp: meta-defs meta-aux split: \nu.split v.split)
```

Remark 26. *PossiblyContingentObjectExistsAxiom is equivalent to the corresponding statement in the embedded logic.*

lemma *PossiblyContingentObjectExistsCheck*:
 $[\neg(\Box(\forall x. (\Box(E!, x^P) \rightarrow \Box(E!, x^P))) \text{ in } v)]$
apply (*simp add: meta-defs forall- ν -def meta-aux split: ν .split v.split*)
using *PossiblyContingentObjectExistsAxiom*
by (*metis ν .simps(5) $\nu\nu$ -def v.simps(1) no- $\sigma\omega$*)
lemma *PossiblyContingentObjectExists*
apply (*auto simp: meta-defs*)
using *PossiblyContingentObjectExistsCheck*
apply (*auto simp: meta-defs forall- ν -def meta-aux split: ν .split v.split*)
by (*metis v.exhaust v.simps(5) v.simps(6)*)

Remark 27. *PossiblyNoContingentObjectExistsAxiom is equivalent to the corresponding statement in the embedded logic.*

lemma *PossiblyNoContingentObjectExistsCheck*:
 $[\neg(\Box(\neg(\forall x. (\Box(E!, x^P) \rightarrow \Box(E!, x^P)))) \text{ in } v)]$
apply (*simp add: meta-defs forall- ν -def meta-aux split: ν .split v.split*)
using *PossiblyNoContingentObjectExistsAxiom* **by** *blast*
lemma *PossiblyNoContingentObjectExists*
using *PossiblyNoContingentObjectExistsCheck*
apply (*auto simp: meta-defs forall- ν -def meta-aux split: ν .split v.split*)
by (*metis v.simps(5) $\nu\nu$ -id*)

11.5 Relations in the Meta-Logic

Remark 28. *Material equality in the embedded logic corresponds to equality in the actual state in the meta-logic.*

lemma *mat-eq-is-eq-dj*:
 $[\forall x. \Box(\Box(F, x^P) \equiv \Box(G, x^P)) \text{ in } v] \longleftrightarrow$
 $((\lambda x. (eval\Pi_1 F) x dj) = (\lambda x. (eval\Pi_1 G) x dj))$
proof
assume *1*: $[\forall x. \Box(\Box(F, x^P) \equiv \Box(G, x^P)) \text{ in } v]$
{
fix *v*
fix *y*
obtain *x* **where** *y-def*: $y = \nu\nu x$ **by** (*metis $\nu\nu$ -id*)
have $(\exists r o_1. \text{Some } r = d_1 F \wedge \text{Some } o_1 = d_\kappa(x^P) \wedge o_1 \in ex1 r v) =$
 $(\exists r o_1. \text{Some } r = d_1 G \wedge \text{Some } o_1 = d_\kappa(x^P) \wedge o_1 \in ex1 r v)$
using *1* **apply** *cut-tac* **by** *meta-solver*
moreover obtain *r* **where** *r-def*: $\text{Some } r = d_1 F$
unfolding *d₁-def* **by** *auto*
moreover obtain *s* **where** *s-def*: $\text{Some } s = d_1 G$
unfolding *d₁-def* **by** *auto*
moreover have $\text{Some } x = d_\kappa(x^P)$
using *d _{κ} -proper* **by** *simp*
ultimately have $(x \in ex1 r v) = (x \in ex1 s v)$
by (*metis option.inject*)
hence $(eval\Pi_1 F) y dj v = (eval\Pi_1 G) y dj v$
using *r-def s-def y-def* **by** (*simp add: d₁.rep-eq ex1-def*)
}
thus $(\lambda x. eval\Pi_1 F x dj) = (\lambda x. eval\Pi_1 G x dj)$
by *auto*
next
assume *1*: $(\lambda x. eval\Pi_1 F x dj) = (\lambda x. eval\Pi_1 G x dj)$
{
fix *y v*
obtain *x* **where** *x-def*: $x = \nu\nu y$
by *simp*
hence $eval\Pi_1 F x dj = eval\Pi_1 G x dj$
using *1* **by** *metis*
moreover obtain *r* **where** *r-def*: $\text{Some } r = d_1 F$
unfolding *d₁-def* **by** *auto*
moreover obtain *s* **where** *s-def*: $\text{Some } s = d_1 G$

```

    unfolding d1-def by auto
  ultimately have (y ∈ ex1 r v) = (y ∈ ex1 s v)
    by (simp add: d1.rep-eq ex1-def νν-νν-id x-def)
  hence [(F, yP) ≡ (G, yP) in v]
    apply cut-tac apply meta-solver
    using r-def s-def by (metis Semantics.dκ-proper option.inject)
}
thus [∀ x. □((F, xP) ≡ (G, xP) in v)]
  using T6 T8 by fast
qed

```

Remark 29. *Material equivalent relations are equal in the embedded logic if and only if they also coincide in all other states.*

```

lemma mat-eq-is-eq-if-eq-forall-j:
  assumes [∀ x. □((F, xP) ≡ (G, xP) in v)]
  shows [F = G in v] ↔
    (∀ s. s ≠ dj → (∀ x. (evalΠ1 F) x s = (evalΠ1 G) x s))
proof
  interpret MetaSolver .
  assume [F = G in v]
  hence F = G
    apply cut-tac unfolding identity-Π1-def by meta-solver
  thus ∀ s. s ≠ dj → (∀ x. evalΠ1 F x s = evalΠ1 G x s)
    by auto
next
  interpret MetaSolver .
  assume ∀ s. s ≠ dj → (∀ x. evalΠ1 F x s = evalΠ1 G x s)
  moreover have ((λ x. (evalΠ1 F) x dj) = (λ x. (evalΠ1 G) x dj))
    using assms mat-eq-is-eq-dj by auto
  ultimately have ∀ s x. evalΠ1 F x s = evalΠ1 G x s
    by metis
  hence evalΠ1 F = evalΠ1 G
    by blast
  hence F = G
    by (metis evalΠ1-inverse)
  thus [F = G in v]
    unfolding identity-Π1-def using Eq1I by auto
qed

```

Remark 30. *Under the assumption that all properties behave in all states like in the actual state the defined equality degenerates to material equality.*

```

lemma assumes ∀ F x s. (evalΠ1 F) x s = (evalΠ1 F) x dj
  shows [∀ x. □((F, xP) ≡ (G, xP) in v)] ↔ [F = G in v]
  by (metis (no-types) MetaSolver.Eq1S assms identity-Π1-def
    mat-eq-is-eq-dj mat-eq-is-eq-if-eq-forall-j)

```

11.6 Lambda Expressions in the Meta-Logic

```

lemma lambda-impl-meta:
  [(λ x. φ x), xP] in v → (∃ y. νν y = νν x → evalo (φ y) dj v)
  unfolding meta-defs νν-def apply transfer using νν-νν-id νν-def by auto

```

```

lemma meta-impl-lambda:
  (∀ y. νν y = νν x → evalo (φ y) dj v) → [(λ x. φ x), xP] in v
  unfolding meta-defs νν-def apply transfer using νν-νν-id νν-def by auto

```

end