Gödel's God in Isabelle/HOL

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A1	Either a property or its negation is positive, but not both:	$\forall\phi[P(\neg\phi) \leftrightarrow \neg P(\phi)]$
A2	A property necessarily implied by a positive property is positive:	$\forall\phi\forall\psi[(P(\phi) \wedge \Box\forall x[\phi(x) \to \psi(x)]) \to P(\psi)]$
T1	Positive properties are possibly exemplified:	$\forall\phi[P(\phi) \to \Diamond\exists x\phi(x)]$
D1	A *God-like* being possesses all positive properties:	$G(x) \leftrightarrow \forall\phi[P(\phi) \to \phi(x)]$
A3	The property of being God-like is positive:	$P(G)$
C	Possibly, God exists:	$\Diamond\exists x G(x)$
A4	Positive properties are necessarily positive:	$\forall\phi[P(\phi) \to \Box\, P(\phi)]$
D2	An *essence* of an individual is a property possessed by it and necessarily implying any of its properties:	$\phi \; ess. \; x \leftrightarrow \phi(x) \wedge \forall\psi(\psi(x) \to \Box\forall y(\phi(y) \to \psi(y)))$
T2	Being God-like is an essence of any God-like being:	$\forall x[G(x) \to G \; ess. \; x]$
D3	*Necessary existence* of an individual is the necessary exemplification of all its essences:	$NE(x) \leftrightarrow \forall\phi[\phi \; ess. \; x \to \Box\exists y\phi(y)]$
A5	Necessary existence is a positive property:	$P(NE)$
T3	Necessarily, God exists:	$\Box\exists x G(x)$

Figure 1: Scott's version of Gödel's ontological argument [12].

1 Introduction

Dana Scott's version [12] (cf. Fig. 1) of Gödel's proof of God's existence [8] is formalized in quantified modal logic KB (QML KB) within the proof assistant Isabelle/HOL. QML KB is modeled as a fragment of classical higher-order logic (HOL); thus, the formalization is essentially a formalization in HOL. The employed embedding of QML KB in HOL is adapting the work of Benzmüller and Paulson [2, 1]. Note that the QML KB formalization employs quantification over individuals and quantification over sets of individuals (properties).

The gaps in Scott's proof have been automated with Sledgehammer [5], performing remote calls to the higher-order automated theorem prover LEO-II [3]. Sledgehammer suggests the Metis [9] calls, which result in proofs that are verified by Isabelle/HOL. For consistency checking, the model finder Nitpick [6] has been employed. The successfull calls to Sledgehammer are deliberately kept as comments in the file for demonstration purposes (normally, they are automatically eliminated by Isabelle/HOL).

Isabelle is described in the textbook by Nipkow, Paulson, and Wenzel [10] and in tutorials available at: http://isabelle.in.tum.de.

1.1 Related Work

The formalization presented here is related to the THF [14] and Coq [4] formalizations at https://github.com/FormalTheology/GoedelGod/tree/master/Formalizations/.

An older ontological argument by Anselm was formalized in PVS by John Rushby [11].

2 An Embedding of QML KB in HOL

The types i for possible worlds and μ for individuals are introduced.

typedecl i — the type for possible worlds
typedecl μ — the type for indiviuals

Possible worlds are connected by an accessibility relation r.

consts $r :: i \Rightarrow i \Rightarrow \mathit{bool}$ (**infixr** r *70*) — accessibility relation r

QML formulas are translated as HOL terms of type $i \Rightarrow \mathit{bool}$. This type is abbreviated as σ.

type-synonym $\sigma = (i \Rightarrow \mathit{bool})$

The classical connectives $\neg, \wedge, \rightarrow$, and $\forall$ (over individuals and over sets of individuals) and $\exists$ (over individuals) are lifted to type σ. The lifted connectives are $m\neg$, $m\wedge$, $m\rightarrow$, $\forall$, and $\exists$ (the latter two are modeled as constant symbols). Other connectives can be introduced analogously. We exemplarily do this for $m\vee$, $m\equiv$, and $mL{=}$ (Leibniz equality on individuals). Moreover, the modal operators $\Box$ and $\Diamond$ are introduced. Definitions could be used instead of abbreviations.

abbreviation *mnot* $:: \sigma \Rightarrow \sigma$ $(m\neg)$ **where** $m\neg\ \varphi \equiv (\lambda w.\ \neg\ \varphi\ w)$
abbreviation *mand* $:: \sigma \Rightarrow \sigma \Rightarrow \sigma$ (**infixr** $m\wedge$ *65*) **where** $\varphi\ m\wedge\ \psi \equiv (\lambda w.\ \varphi\ w \wedge \psi\ w)$
abbreviation *mor* $:: \sigma \Rightarrow \sigma \Rightarrow \sigma$ (**infixr** $m\vee$ *70*) **where** $\varphi\ m\vee\ \psi \equiv (\lambda w.\ \varphi\ w \vee \psi\ w)$
abbreviation *mimplies* $:: \sigma \Rightarrow \sigma \Rightarrow \sigma$ (**infixr** $m\rightarrow$ *74*) **where** $\varphi\ m\rightarrow\ \psi \equiv (\lambda w.\ \varphi\ w \longrightarrow \psi\ w)$
abbreviation *mequiv*$:: \sigma \Rightarrow \sigma \Rightarrow \sigma$ (**infixr** $m\equiv$ *76*) **where** $\varphi\ m\equiv\ \psi \equiv (\lambda w.\ \varphi\ w \longleftrightarrow \psi\ w)$
abbreviation *mforall* $:: ('a \Rightarrow \sigma) \Rightarrow \sigma$ $(\forall)$ **where** $\forall\ \ \Phi \equiv (\lambda w.\ \forall x.\ \Phi\ x\ w)$
abbreviation *mexists* $:: ('a \Rightarrow \sigma) \Rightarrow \sigma$ $(\exists)$ **where** $\exists\ \ \Phi \equiv (\lambda w.\ \exists x.\ \Phi\ x\ w)$
abbreviation *mLeibeq* $:: \mu \Rightarrow \mu \Rightarrow \sigma$ (**infixr** $mL{=}$ *90*) **where** $x\ mL{=}\ y \equiv \forall(\lambda\varphi.\ (\varphi\ x\ m\rightarrow\ \varphi\ y))$
abbreviation *mbox* $:: \sigma \Rightarrow \sigma$ $(\Box)$ **where** $\Box\ \varphi \equiv (\lambda w.\ \forall v.\ \ w\ r\ v \longrightarrow \varphi\ v)$
abbreviation *mdia* $:: \sigma \Rightarrow \sigma$ $(\Diamond)$ **where** $\Diamond\ \varphi \equiv (\lambda w.\ \exists v.\ w\ r\ v \wedge \varphi\ v)$

For grounding lifted formulas, the meta-predicate *valid* is introduced.

abbreviation *valid* $:: \sigma \Rightarrow \mathit{bool}$ ([-]) **where** $[p] \equiv \forall w.\ p\ w$

3 Gödel's Ontological Argument

Constant symbol P (Gödel's 'Positive') is declared.

consts $P :: (\mu \Rightarrow \sigma) \Rightarrow \sigma$

The meaning of P is restricted by axioms *A1(a/b)*: $\forall\phi[P(\neg\phi) \leftrightarrow \neg P(\phi)]$ (Either a property or its negation is positive, but not both.) and *A2*: $\forall\phi\forall\psi[(P(\phi) \wedge \Box\forall x[\phi(x) \rightarrow \psi(x)]) \rightarrow P(\psi)]$ (A property necessarily implied by a positive property is positive).

axiomatization where
A1a: $[\forall\,(\lambda\Phi.\ P\ (\lambda x.\ m\neg\ (\Phi\ x))\ m{\rightarrow}\ m\neg\ (P\ \Phi))]$ **and**
A1b: $[\forall\,(\lambda\Phi.\ m\neg\ (P\ \Phi)\ m{\rightarrow}\ P\ (\lambda x.\ m\neg\ (\Phi\ x)))]$ **and**
A2: $[\forall\,(\lambda\Phi.\ \forall\,(\lambda\Psi.\ (P\ \Phi\ m{\wedge}\ \Box\ (\forall\,(\lambda x.\ \Phi\ x\ m{\rightarrow}\ \Psi\ x)))\ m{\rightarrow}\ P\ \Psi))]$

We prove theorem T1: $\forall\phi[P(\phi) \rightarrow \Diamond\exists x\phi(x)]$ (Positive properties are possibly exemplified). T1 is proved directly by Sledgehammer with command *sledgehammer* [*provers* = *remote-leo2*]. Sledgehammer suggests to call Metis with axioms A1a and A2. Metis sucesfully generates a proof object that is verified in Isabelle/HOL's kernel.

theorem *T1*: $[\forall\,(\lambda\Phi.\ P\ \Phi\ m{\rightarrow}\ \Diamond\ (\exists\ \Phi))]$
— sledgehammer [provers = remote_leo2]
⟨*proof*⟩

Next, the symbol G for 'God-like' is introduced and defined as $G(x) \leftrightarrow \forall\phi[P(\phi) \rightarrow \phi(x)]$ (A God-like being possesses all positive properties).

definition $G :: \mu \Rightarrow \sigma$ **where** $G = (\lambda x.\ \forall\,(\lambda\Phi.\ P\ \Phi\ m{\rightarrow}\ \Phi\ x))$

Axiom *A3* is added: $P(G)$ (The property of being God-like is positive). Sledgehammer and Metis then prove corollary C: $\Diamond\exists x G(x)$ (Possibly, God exists).

axiomatization where *A3*: $[P\ G]$

corollary C: $[\Diamond\ (\exists\ G)]$
— sledgehammer [provers = remote_leo2]
⟨*proof*⟩

Axiom *A4* is added: $\forall\phi[P(\phi) \rightarrow \Box\ P(\phi)]$ (Positive properties are necessarily positive).

axiomatization where *A4*: $[\forall\,(\lambda\Phi.\ P\ \Phi\ m{\rightarrow}\ \Box\ (P\ \Phi))]$

Symbol *ess* for 'Essence' is introduced and defined as

$$\phi\ ess.\ x \leftrightarrow \phi(x) \wedge \forall\psi(\psi(x) \rightarrow \Box\forall y(\phi(y) \rightarrow \psi(y)))$$

(An *essence* of an individual is a property possessed by it and necessarily implying any of its properties).

definition *ess* $:: (\mu \Rightarrow \sigma) \Rightarrow \mu \Rightarrow \sigma$ (**infixr** *ess 85*) **where**
$\Phi\ ess\ x = \Phi\ x\ m{\wedge}\ \forall\,(\lambda\Psi.\ \Psi\ x\ m{\rightarrow}\ \Box\ (\forall\,(\lambda y.\ \Phi\ y\ m{\rightarrow}\ \Psi\ y)))$

Next, Sledgehammer and Metis prove theorem *T2*: $\forall x[G(x) \rightarrow G\ ess.\ x]$ (Being God-like is an essence of any God-like being).

theorem *T2*: $[\forall\,(\lambda x.\ G\ x\ m{\rightarrow}\ G\ ess\ x)]$
— sledgehammer [provers = remote_leo2]
⟨*proof*⟩

Symbol *NE*, for 'Necessary Existence', is introduced and defined as

$$NE(x) \leftrightarrow \forall\phi[\phi\ ess.\ x \rightarrow \Box\exists y\phi(y)]$$

(Necessary existence of an individual is the necessary exemplification of all its essences).

definition $NE :: \mu \Rightarrow \sigma$ **where** $NE = (\lambda x.\ \forall (\lambda\Phi.\ \Phi\ ess\ x\ m{\rightarrow}\ \Box\ (\exists\ \Phi)))$

Moreover, axiom *A5* is added: $P(NE)$ (Necessary existence is a positive property).

axiomatization where *A5*: $[P\ NE]$

The B axiom (symmetry) for relation r is stated. B is needed only for proving theorem T3 and for corollary C2.

axiomatization where *sym*: $x\ r\ y \longrightarrow y\ r\ x$

Finally, Sledgehammer and Metis prove the main theorem *T3*: $\Box\exists x G(x)$
(Necessarily, God exists).

theorem *T3*: $[\Box\ (\exists\ G)]$
— sledgehammer [provers = remote_leo2]
⟨*proof*⟩

Surprisingly, the following corollary can be derived even without the T axiom (reflexivity).

corollary *C2*: $[\exists\ G]$
— sledgehammer [provers = remote_leo2]
⟨*proof*⟩

The consistency of the entire theory is confirmed by Nitpick.

lemma *True* **nitpick** [*satisfy*, *user-axioms*, *expect* = *genuine*] ⟨*proof*⟩

4 Additional Results on Gödel's God.

Gödel's God is flawless: (s)he does not have non-positive properties.

theorem *Flawlessness*: $[\forall (\lambda\Phi.\ \forall (\lambda x.\ (G\ x\ m{\rightarrow}\ (m\neg\ (P\ \Phi)\ m{\rightarrow}\ m\neg\ (\Phi\ x)))))]$
— sledgehammer [provers = remote_leo2]
⟨*proof*⟩

There is only one God: any two God-like beings are equal.

theorem *Monotheism*: $[\forall (\lambda x.\forall (\lambda y.\ (G\ x\ m{\rightarrow}\ (G\ y\ m{\rightarrow}\ (x\ mL{=}\ y)))))]$
— sledgehammer [provers = remote_leo2]
⟨*proof*⟩

5 Modal Collapse

Gödel's axioms have been criticized for entailing the so-called modal collapse. The prover Satallax [7] confirms this. However, sledgehammer is not able to determine which axioms, definitions and previous theorems are used by Satallax; hence it suggests to call Metis using everything, but this (unsurprinsingly) fails. Attempting to use 'Sledegehammer min' to minimize Sledgehammer's suggestion does not work. Calling Metis with *T2*, *T3* and *ess-def* also does not work.

lemma *MC*: $[\forall (\lambda\Phi.(\Phi\ m{\rightarrow}\ (\Box\ \Phi)))]$
— sledgehammer [provers = remote_satallax]
— by (metis T2 T3 ess_def)
⟨*proof*⟩

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References

[1] C. Benzmüller and L. Paulson. Exploring properties of normal multimodal logics in simple type theory with LEO-II. In *Reasoning in Simple Type Theory — Festschrift in Honor of Peter B. Andrews on His 70th Birthday*, Studies in Logic, Mathematical Logic and Foundations, pages 386–406. College Publications, 2008. (Superseded by 2013 article in Logica Universalis).

[2] C. Benzmüller and L. Paulson. Quantified multimodal logics in simple type theory. *Logica Universalis*, 7(1):7–20, 2013.

[3] C. Benzmüller, L. C. Paulson, F. Theiss, and A. Fietzke. LEO-II – A cooperative automatic theorem prover for classical higher-order logic (system description). In *Proc. of IJCAR 2008*, volume 5195 of *LNAI*, pages 162–170. Springer, 2008.

[4] Y. Bertot and P. Casteran. *Interactive Theorem Proving and Program Development.* Springer, 2004.

[5] J. C. Blanchette, S. Böhme, and L. C. Paulson. Extending Sledgehammer with SMT solvers. *Journal of Automated Reasoning*, 51(1):109–128, 2013.

[6] J. C. Blanchette and T. Nipkow. Nitpick: A counterexample generator for higher-order logic based on a relational model finder. In *Proc. of ITP 2010*, volume 6172 of *LNCS*, pages 131–146. Springer, 2010.

[7] C. E. Brown. Satallax: An automatic higher-order prover. In *Proc. of IJCAR 2012*, volume 7364 of *LNAI*, pages 111–117. Springer, 2012.

[8] K. Gödel. Appendix A. Notes in Kurt Gödel's Hand. In Sobel [13], pages 144–145.

[9] J. Hurd. First-order proof tactics in higher-order logic theorem provers. In *Design and Application of Strategies/Tactics in Higher Order Logics*, pages 56–68, Sept. 2003. Tech. Rep. NASA/CP-2003-212448.

[10] T. Nipkow, L. C. Paulson, and M. Wenzel. *Isabelle/HOL — A Proof Assistant for Higher-Order Logic*, volume 2283 of *LNCS*. Springer, 2002.

[11] J. Rushby. The Ontological Argument in PVS. In *CAV Workshop "Fun With Formal Methods'*, volume 13, St. Petersburg, Russia, July 2013.

[12] D. S. Scott. Appendix B: Notes in Dana Scott's Hand. In Sobel [13], pages 145–146.

[13] J. H. Sobel. *Logic and Theism: Arguments for and Against Beliefs in God.* Cambridge University Press, 2004.

[14] G. Sutcliffe and C. Benzmüller. Automated reasoning in higher-order logic using the TPTP THF infrastructure. *Journal of Formalized Reasoning*, 3(1):1–27, 2010.