Meta-Logical Reasoning in Higher-Order Logic

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Abstract
The terms and formulas of the FOL language are defined as the datatypes \texttt{tm} and \texttt{fm}, respectively. Variables are indexed using de Bruijn indices. The semantics of the language is defined using the function \texttt{sem} where \texttt{e} is the environment, i.e. a mapping of variables to elements of the universe \texttt{u}, \texttt{f} maps constants to elements of \texttt{u}, and \texttt{g} gives the semantics of the predicates. Most of the cases of \texttt{sem} should be self-explanatory, but the \texttt{Uni} case is complicated. The details are not important here, but it uses the universal quantifier (!) to consider all values of the universe \texttt{u}. It also uses the lambda operator (\%) to keep track of the indices of the variables.

Examples of Meta-Logical Reasoning
By using HOL as the meta-language for FOL it is possible to make use of proof assistants such as Isabelle to reason about certain properties of FOL. For example, let \texttt{syn} be a proof system for FOL implemented as a predicate in Isabelle of type \texttt{tm \rightarrow bool} (an inductive definition). If it is sound then we can prove this in Isabelle as the theorem \texttt{syn fml \rightarrow \forall e f g. sem e f g fml}. Likewise completeness \texttt{(!e f g. sen e f g fml) \rightarrow syn fml} can be proved if the proof system is indeed complete. For example, in Berghofer (2007) a natural deduction proof system for FOL is proven sound and complete. A tool for teaching logic based on natural deduction has recently been developed and proved sound by Villadsen (2015).

Meta-logical reasoning using the formalized semantics also enables formal proofs of sentences using only the semantics of the object language. For example, we wish to show that the sentence \forall x. \forall y. P(x, y) is valid. We can prove this by first fixing two arbitrary elements \texttt{u, w} of the universe and show \texttt{P(y, x) \rightarrow P(x, y)} for an arbitrary environment updated to map variable \texttt{x} to \texttt{u} and \texttt{y} to \texttt{w}, and then use the fact that any denotation \texttt{g} of predicates maps \texttt{(P, u, w)} to either true or false. In both cases \texttt{P(y, x)} holds. This proof sketch can then be extended to a readable proof in Isabelle. The sentence can even be proved automatically in Isabelle using the formalized semantics:

\texttt{theorem "\forall e f g. sen e f g (Uni (Uni (Imp (Pre "P" (Var 0))) \& (Var 1)))" by auto}

On the other hand the sentence \forall x. \forall y. P(x, y) \rightarrow P(y, x) is not valid. Therefore we can ask Isabelle to search for a counterexample, using the \texttt{nitpick} command, and it is able to find one.

Finally, the approach we have presented can even be used with HOL as the object language, that is, the semantics of HOL and a proof system for HOL can also be formalized in HOL, most extensively by Kumar (2014), although of course self-verification is not possible due to the second incompleteness theorem. Paulson (2014) has recently formalized the incompleteness theorems in Isabelle.

References