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Skolemization in Simple Type Theory: the Logical and the Theoretical Points of View

Gilles Dowek*

Peter Andrews has proposed, in 1971, the problem of finding an analog of the Skolem theorem for Simple Type Theory. A first idea lead to a naive rule that worked only for Simple Type Theory with the axiom of choice and the general case has only been solved, more than ten years later, by Dale Miller [9, 10]. More recently, we have proposed with Thérèse Hardin and Claude Kirchner [7] a new way to prove analogs of the Miller theorem for different, but equivalent, formulations of Simple Type Theory.

In this paper, that does not contain new technical results, I try to show that the history of the skolemization problem and of its various solutions is an illustration of a tension between two points of view on Simple Type Theory: the *logical* and the *theoretical* points of view.

1 Skolemization

1.1 The Skolem theorem

Let \mathcal{T} be a theory in first-order predicate logic containing an axiom of the form

$$\forall x_1 \dots \forall x_n \exists y A$$

and \mathcal{T}' be the theory obtained by replacing this axiom by

$$\forall x_1 \dots \forall x_n ((f(x_1, \dots, x_n)/y)A)$$

where f is a function symbol not used in \mathcal{T} . Then, the Skolem theorem asserts that the theory \mathcal{T}' is a conservative extension of \mathcal{T} and, in particular, that one theory is contradictory if and only if the other is.

1.2 Extending Skolem theorem to Simple Type Theory

The Skolem theorem plays a key role in automated theorem proving because it permits to eliminate quantifier alternation in the proposition to be proved, or refuted, and this alternation is often delicate to manage. This explains why,

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in 1971, seeking for a generalization of the Resolution method to Simple Type Theory [2], Peter Andrews has proposed the problem of finding an analog of the Skolem theorem for Simple Type Theory.

Following the Skolem theorem for first-order predicate logic, we can try to replace an axiom of the form

$$\forall x_1 \dots \forall x_n \exists y A$$

where x_1, \dots, x_n and y are variables of type T_1, \dots, T_n and U , by

$$\forall x_1 \dots \forall x_n ((f x_1 \dots x_n)/y)A$$

where f is now a new constant of type $T_1 \rightarrow \dots \rightarrow T_n \rightarrow U$. Unfortunately, the theory \mathcal{T}' obtained this way is not always a conservative extension of the theory \mathcal{T} . For instance, it is not possible to prove the proposition $\exists g \forall x (P x (g x))$ from the axiom $\forall x \exists y (P x y)$, because, as proved again by Peter Andrews in 1972 [3], the axiom of choice

$$(\forall x \exists y (P x y)) \Rightarrow (\exists g \forall x (P x (g x)))$$

is not provable in Simple Type Theory. But this proposition is obviously provable from the skolemized form of this axiom: $\forall x (P x (f x))$. Thus, although this naive skolemization can be used in Simple Type Theory extended with the axiom of choice, it cannot be used in the usual formulation of Simple Type Theory, without the axiom of choice.

A more restricted form of skolemization has been proposed in 1983 by Dale Miller. In the Miller theorem, the Skolem symbol f is not only given the type $T_1 \rightarrow \dots \rightarrow T_n \rightarrow U$ but also the arity $\langle T_1, \dots, T_n, U \rangle$ and, unlike the usual symbols of a functional type, the Skolem symbols are not terms *per se*. To form a term with a Skolem symbol f of arity $\langle T_1, \dots, T_n, U \rangle$, it is necessary to apply it to terms t_1, \dots, t_n of type T_1, \dots, T_n , called the *necessary arguments* of the symbol f . This reflects the intuition that, in a model of the negation of the axiom of choice, we may have for each n -uple t_1, \dots, t_n the object $(f t_1 \dots t_n)$, without having the function f itself as an object.

As it is not a term, the symbol f cannot be used as a witness to prove the proposition $\exists g \forall x (P x (g x))$. However, this restriction is not sufficient, because, although the symbol f cannot be used as a witness, the term $\lambda z (f z)$, can, yielding, after normalization, the same result: $\forall x (P x (f x))$. This explains why Miller has introduced a second restriction: that the variables free in the necessary arguments of a Skolem symbol cannot be bound by a λ -abstraction, higher in a term substituted for a variable in a quantifier rule.

With these two restrictions, Miller has been able to give a syntactic proof of an analogous of the Skolem theorem: any proof using the axiom

$$\forall x_1 \dots \forall x_n ((f x_1 \dots x_n)/y)A$$

and whose conclusion does not use the symbol f can be transformed into a proof using the axiom

$$\forall x_1 \dots \forall x_n \exists y A$$

2 The logical and the theoretical point of view

Simple Type Theory is otherwise known as *higher-order logic*. This duality of names reveals that this formalism is sometimes seen as a theory and sometimes as a logic. As a theory, it should be compared to other theories, such as arithmetic or set theory. As a logic, to other logics, and in particular to first-order predicate logic, that, historically, is a restriction of it.

From the logical point of view, it is natural to try to *extend* the theorems and algorithms known for first-order predicate logic, such as the Gödel completeness theorem, the Skolem theorem, the Resolution method, ... to higher-order predicate logic. But, from the theoretical point of view, it is more natural to try to express Simple Type Theory as an axiomatic theory in first-order predicate logic and *apply* these theorems and algorithms to this particular theory.

This tension between the logical and the theoretical point of view is illustrated in a 1968 discussion between J. Alan Robinson and Martin Davis [11, 5]. Robinson calls first-order predicate logic: “the restricted predicate calculus” and higher-order logic: “the full predicate calculus”, while Davis, replying that it is a simple matter to express Simple Type Theory as a theory in first-order predicate logic, calls such a theory expressed in first-order predicate logic a “theory with standard formulation”.

The logical point of view has dominated the history of Simple Type Theory: Henkin models, Higher-order resolution, ... have been designed specifically for Simple Type Theory and not for a class of theories formulated in first-order predicate logic, among which Simple Type Theory is one instance. It is only recently that presentations of Simple Type Theory in first-order predicate logic have shed a new light on Henkin models, as anticipated by Martin Davis [5], on higher-order unification, on proof search algorithms, on cut elimination theorems, on functional interpretations of constructive proofs, ... and on the Miller theorem.

Indeed, as shown in [7], expressing Simple Type Theory as a theory in first-order predicate logic allows to apply the Skolem theorem and this way to reconstruct the Miller theorem.

3 Simple Type Theory as a theory in first-order predicate logic

We shall express Simple Type Theory as a theory in many-sorted first-order predicate logic with equality. If a single-sorted formulation were needed, the usual relativization method could be applied.

3.1 Sorts

As, in Simple Type Theory, functions and predicates are objects, the sorts of the theory are not only the base types ι and o of Simple Type Theory but all its types: $\iota, o, \iota \rightarrow \iota, \iota \rightarrow o, o \rightarrow o, \dots$

As usual in many-sorted first-order predicate logic, terms are assigned a sort and function and predicate symbols are assigned a tuple of sort called an *arity* or a *rank*. If f is a function symbol of arity $\langle T_1, \dots, T_n, U \rangle$ and t_1, \dots, t_n are terms of sort T_1, \dots, T_n , then $f(t_1, \dots, t_n)$ is a term of sort U and if P is a predicate symbol of arity $\langle T_1, \dots, T_n \rangle$ and t_1, \dots, t_n are terms of sort T_1, \dots, T_n , then $P(t_1, \dots, t_n)$ is an atomic proposition.

3.2 Symbols

It is well-known that making a predicate P an object requires to introduce a copula \in and write $a \in P$ what was previously written $P(a)$. In the same way making a function f an object requires to introduce an application symbol α and write $\alpha(f, a)$ what was previously written $f(a)$.

In Simple Type Theory, we need a function symbol $\alpha_{T,U}$ of arity $\langle T \rightarrow U, T, U \rangle$ for each pair of sorts T, U and a single predicate symbol ε of arity $\langle o \rangle$ to promote a term t of sort o to a proposition $\varepsilon(t)$.

For instance, if P is a term of sort $T \rightarrow o$ and t a term of sort T , then the proposition usually written $P(t)$ is not written $t \in P$, like in set theory, but $\varepsilon(\alpha_{T,o}(P, t))$ where P is first applied to t using the function symbol $\alpha_{T,o}$ to build a term of sort o , that is then promoted to a proposition using the predicate symbol ε . In the same way, the proposition usually written $\forall P (P \Rightarrow P)$ is written $\forall p (\varepsilon(p) \Rightarrow \varepsilon(p))$.

Then, we need symbols to construct terms expressing functions and predicates. Introducing the binding symbol λ is not possible in first-order predicate logic and we have to use a first-order encoding of λ -calculus. A simple solution is to use the combinators S and K . Thus, for each triple of sorts T, U, V , we introduce a constant $S_{T,U,V}$ of sort $(T \rightarrow U \rightarrow V) \rightarrow (T \rightarrow U) \rightarrow T \rightarrow V$ and for each pair of sorts T, U , we introduce a constant $K_{T,U}$ of sort $T \rightarrow U \rightarrow T$. Finally, we need similar combinators to build terms of sort o . Thus, we introduce constants $\dot{=}_T$ of sort $T \rightarrow T \rightarrow o$, $\dot{\top}$ and $\dot{\perp}$ of sorts o , $\dot{\rightarrow}$ of sort $o \rightarrow o$, $\dot{\wedge}$, $\dot{\vee}$ and $\dot{\Rightarrow}$ of sort $o \rightarrow o \rightarrow o$, $\dot{\forall}_T$ and $\dot{\exists}_T$ of sort $(T \rightarrow o) \rightarrow o$. Of course, some of these symbols are redundant and could be defined from others using de Morgan's law. It is also possible to define all these symbols from equality $\dot{=}_T$, following the idea of Leon Henkin and Peter Andrews [8, 1].

Indices may be omitted when they can be reconstructed from the context.

3.3 Axioms

Finally, we need axioms expressing the meaning of these symbols. Besides the axioms of equality, we take the axioms

$$\begin{aligned} \forall x \forall y \forall z (\alpha(\alpha(\alpha(S, x), y), z) &= \alpha(\alpha(x, z), \alpha(y, z))) \\ \forall x \forall y (\alpha(\alpha(K, x), y) &= x) \\ \forall x \forall y (\varepsilon(\alpha(\alpha(\dot{=}, x), y)) &\Leftrightarrow (x = y)) \\ \varepsilon(\dot{\top}) &\Leftrightarrow \top \end{aligned}$$

$$\begin{aligned}
\varepsilon(\perp) &\Leftrightarrow \perp \\
\forall x (\varepsilon(\alpha(\dot{\cdot}, x)) &\Leftrightarrow \neg\varepsilon(x)) \\
\forall x \forall y (\varepsilon(\alpha(\alpha(\dot{\wedge}, x), y)) &\Leftrightarrow (\varepsilon(x) \wedge \varepsilon(y))) \\
\forall x \forall y (\varepsilon(\alpha(\alpha(\dot{\vee}, x), y)) &\Leftrightarrow (\varepsilon(x) \vee \varepsilon(y))) \\
\forall x \forall y (\varepsilon(\alpha(\alpha(\dot{\Rightarrow}, x), y)) &\Leftrightarrow (\varepsilon(x) \Rightarrow \varepsilon(y))) \\
\forall x (\varepsilon(\alpha(\dot{\forall}, x)) &\Leftrightarrow \forall y \varepsilon(\alpha(x, y))) \\
\forall x (\varepsilon(\alpha(\dot{\exists}, x)) &\Leftrightarrow \exists y \varepsilon(\alpha(x, y)))
\end{aligned}$$

To these axioms, we may add, as usual, the extensionality axioms, the axiom of infinity, the description axiom and the axiom of choice.

To recall the choice we have made to express terms with combinators, we call this theory *HOL-SK*.

3.4 Properties

An easy induction on the structure of t permits to prove that for each term t there exists a term u such that the proposition

$$\alpha(u, x) = t$$

is provable. The term u is often written $\hat{\lambda}x t$. In the same way, an easy induction on the structure of P permits to prove that for each proposition P there exists a term u such that the proposition

$$\varepsilon(u) \Leftrightarrow P$$

is provable.

This way, we can translate all the terms of the usual formulation of Simple Type Theory with λ -calculus to terms of HOL-SK and prove that if t is a term of sort o and t' its translation, then t is provable in the usual formulation of Simple Type theory if and only if $\varepsilon(t')$ is provable in HOL-SK. However, this theorem requires that the extensionality axioms are added to both theories, because the combinators S and K do not simulate λ -calculus exactly, but only up to extensionality.

4 Skolemization

As a consequence of the Skolem theorem, we get that if \mathcal{T} is a theory containing an axiom of the form

$$\forall x_1 \dots \forall x_n \exists y A$$

where x_1, \dots, x_n and y are variables of sorts T_1, \dots, T_n and U , and \mathcal{T}' is the theory obtained by replacing this axiom by

$$\forall x_1 \dots \forall x_n ((f(x_1, \dots, x_n)/y)A)$$

then $\text{HOL-SK} \cup \mathcal{T}'$ is a conservative extension of $\text{HOL-SK} \cup \mathcal{T}$.

The symbol f is a function symbol of arity $\langle T_1, \dots, T_n, U \rangle$ and not a constant of sort $T_1 \rightarrow \dots \rightarrow T_n \rightarrow U$, first because the Skolem theorem for first-order predicate logic introduces a function symbol and not a constant and then because it ignores the internal structure of sorts. Thus, the symbol f alone is not a term, and the term obtained by applying the symbol f to the terms t_1, \dots, t_n is the term $f(t_1, \dots, t_n)$ and not the ill-formed term $\alpha(\dots\alpha(f, t_1), \dots, t_n)$. In contrast, when the sort U has the form $V \rightarrow W$, the term $f(t_1, \dots, t_n)$ can be further applied to a term t_{n+1} using the application symbol: $\alpha(f(t_1, \dots, t_n), t_{n+1})$.

In short, the Skolem symbols are not at the level of the symbols S or K , but at the level of the symbols $\alpha_{T,U}$.

We prove this way an analogous of the Miller theorem for HOL-SK. For this formulation Miller's second condition vanishes as there is no binder λ . All that remains is the first condition: the fact that Skolem symbols must be applied. Notice however that the term $\hat{\lambda}x t$ cannot be defined for all terms t containing the symbol f , but only those that do not have an occurrence of the variable x in an argument of the symbol f .

An advantage of expressing Simple Type Theory as a theory in first-order predicate logic is that the proof of the Miller theorem is simplified as it is then proved as a consequence of the Skolem theorem. Moreover this shows that arities are not a feature of the Skolem symbols only, but that all function symbols have arities, in particular the symbols $\alpha_{T,U}$ and the Skolem symbols.

5 Miller's second condition

We may wonder if it is possible to go one step further and reconstruct Miller's second condition as a consequence of the Skolem theorem for first-order predicate logic. As we shall see, this is possible but this requires to use a more precise first-order encoding of the λ -calculus: the λ -calculus with nameless dummies introduced by Nicolaas de Bruijn [6].

5.1 De Bruijn indices

In a λ -term, we may add, to each occurrence of a bound variable, a natural number expressing the number of abstractions separating the occurrence from its binder. For instance, adding indices to the term

$$\lambda x \lambda y (x \lambda z (y x z))$$

yields

$$\lambda x \lambda y (x^2 \lambda z (y^2 x^3 z^1))$$

Indeed, the index of the occurrence of the variable z is 1 because the binder λz is just one level above in the term, while the index of the second occurrence of the variable x is 3 as the the binder λx is three levels above. Once the indices

are added this way, the names of the bound variables are immaterial and can be dropped. We thus get the term

$$\lambda\lambda (-^2 \lambda (-^2 -^3 -^1))$$

Notice that the term $\lambda x\lambda y (x \lambda z (y x z))$ is closed but that its subterm $\lambda y (x \lambda z (y x z))$ contains a free variable x . In the same way, in the term $\lambda\lambda (-^2 \lambda (-^2 -^3 -^1))$ all the de Bruijn indices refer to a binder, but its subterm $\lambda (-^2 \lambda (-^2 -^3 -^1))$ contain two “free indices”, that exceeded the number of binders above them, and correspond to the former occurrences of the variable x .

The λ -calculus with de Bruijn indices is a first-order language as, once variables names have been dropped, the symbol λ is not a binder anymore. This language is formed with an infinite number of constants $-^1, -^2, -^3, \dots$, a binary function symbol α for application and a unary function symbol λ . Closed terms, such as $\lambda (-^2 \lambda (-^2 -^3 -^1))$ or $-^1$, may contain free indices, exceeding the number of binders above them.

5.2 Sorts

When type-checking an open λ -term *à la* Church, *i.e.* with explicitly typed bound variables, for instance

$$\lambda y_{((\iota \rightarrow \iota) \rightarrow \iota) \rightarrow \iota \rightarrow \iota} (x \lambda z_{\iota} (y x z))$$

it is necessary to have a context defining the type of the free variables such as x . Indeed, if x is assigned the type $(\iota \rightarrow \iota) \rightarrow \iota$, then the term is well-typed, but not if it is assigned, for instance, the type ι .

In the same way, when typing a term that may contains free de Bruijn indices, even if this term is closed (*i.e.* does not contain named variables), we need a context defining the types of the de Bruijn indices exceeding the number of binders above them. This context is a finite list of types: the type of the indices exceeding by 1 the number of binders above them, that of the indices exceeding by 2 the number of binders above them, ... For instance the term

$$\lambda_{((\iota \rightarrow \iota) \rightarrow \iota) \rightarrow \iota \rightarrow \iota} (-^2 \lambda_{\iota} (-^2 -^3 -^1))$$

has type $((\iota \rightarrow \iota) \rightarrow \iota) \rightarrow \iota \rightarrow \iota$ in the context $[(\iota \rightarrow \iota) \rightarrow \iota]$.

Thus, even if it is closed, a term t can be assigned a type T , only relatively to a context Γ . In other words, it can be absolutely assigned an ordered pair formed with a context Γ and a type T . We write such a pair $\Gamma \vdash T$.

When we express Simple Type Theory as a first-order theory, using the λ -calculus with de Bruijn indices as a first-order encoding of the λ -calculus, the sort are not just the simple types, like in HOL-SK, but such pairs $\Gamma \vdash T$ formed with a list Γ of simple types and a simple type T .

In this formulation, the quantified variables, in contrast to the λ -abstracted ones, are not replaced by de Bruijn indices but, as in all theories expressed in first-order predicate logic, they are kept as standard named variables and they are assigned a sort of the form $\vdash T$, where the context is the empty list.

The last step of the construction of this theory would be to introduce explicit substitutions, hence its name *HOL- $\lambda\sigma$* . I do not want to go into these details here and the interested reader can refer to [7]. But, I want to insist on two points. First, the fact that this theory is *intentionally* equivalent to the usual presentation of Simple Type Theory with λ -calculus, *i.e.* even if the extensionality axioms are not assumed. Second, that, as explained above, the sorts are pairs $\Gamma \vdash T$, *i.e.* that they contain scoping information. In particular terms of a sort $\vdash T$, with an empty context, are de Bruijn-closed, *i.e.* they do not contain indices that may be bound higher in the term by a λ -abstraction.

5.3 Skolemization

As a consequence of the Skolem theorem, we get that if \mathcal{T} is a theory containing an axiom of the form

$$\forall x_1 \dots \forall x_n \exists y A$$

where x_1, \dots, x_n and y are variables of sort $\vdash T_1, \dots, \vdash T_n$ and $\vdash U$, and \mathcal{T}' is the theory obtained by replacing this axiom by

$$\forall x_1 \dots \forall x_n ((f(x_1, \dots, x_n)/y)A)$$

then $\text{HOL-}\lambda\sigma \cup \mathcal{T}'$ is a conservative extension of $\text{HOL-}\lambda\sigma \cup \mathcal{T}$. The symbol f is a function symbol of arity $\langle \vdash T_1, \dots, \vdash T_n, \vdash U \rangle$. Thus, not only f is a function symbol, but a function symbol whose arguments must not contain indices that may be bound by a λ -abstraction higher in a term. We get this way exactly Miller's conditions. The first is rephrased as the fact that f is a function symbol and the second as the fact that the arguments of these function symbol must have a sort with an empty context.

We obtain this way an alternative proof of the Miller theorem for $\text{HOL-}\lambda\sigma$, as consequence of the Skolem theorem.

A difficult point in the Miller theorem is the discrepancy between the general formation rules for the terms and the propositions and the more restricted ones for the terms substituted for variables in quantifier rules. As we have seen, the variables free in the necessary arguments of the Skolem symbols cannot be bound in a term substituted for a variable. But this restriction does not apply to the terms and propositions in general, because, if it did, the skolemized axiom itself would not be well-formed, as the arguments of the Skolem symbol in this skolemized axiom are universally bound variables.

In $\text{HOL-}\lambda\sigma$ the situation is slightly different. The formation rules for the terms substituted for variables in quantifier rules are the same as those of the other terms. But the λ -bound variables and the quantified variables are treated differently. As we have seen, the λ -bound variables are replaced by de Bruijn indices, but the quantified variables are kept as named variables, as in all theories expressed in first-order predicate logic. Thus the λ -bound variables cannot appear in the arguments of a Skolem symbol but the quantified variables can and, this way, the skolemized axiom is well-formed.

6 From the theoretical point of view

With this example of skolemization, we have seen two advantages of the theoretical point of view on Simple Type Theory. First the proofs of the theorems are simplified, because we can take advantage of having already proved similar theorems for first-order predicate logic. Then some difficult points of these theorems are explained.

We can mention several other theorems and algorithms that have been simplified and explained this way. The Henkin completeness theorem, already mentioned in 1968 by Martin Davis, independence results, in particular of the extensionality axioms, cut elimination theorems, both model-based ones and reduction-based ones, proof search algorithms and the functional interpretation of constructive proofs.

This succession of points of view on Simple Type Theory is itself an example of a common back and forth movement in the development of science: first, new objects and new results are discovered, breaking with the old framework, they are supposed not to fit in. Then, after a possible evolution of the general framework, these new objects are integrated back. We may try to understand what kind of evolution of first-order predicate logic, the integration of Simple Type Theory requires or suggests.

The first evolution is the shift from the single-sorted first-order predicate logic to the many-sorted one. Although it is always possible to relativize a many-sorted theory to a single-sorted one, the natural framework to express Simple Type Theory is many-sorted first-order predicate logic. It is interesting to see that early papers on many-sorted first-order predicate logic, *e.g.* [12], already motivate the introduction of many-sorted first-order predicate logic by the will to express Simple Type Theory in it.

A second evolution is to take into account the possibility to consider terms and propositions up to reduction. The axioms of HOL-SK (and those of HOL- $\lambda\sigma$) can easily be transformed into rewrite rules:

$$\begin{aligned} \alpha(\alpha(\alpha(S, x), y), z) &\longrightarrow \alpha(\alpha(x, z), \alpha(y, z)) \\ \alpha(\alpha(K, x), y) &\longrightarrow x \\ \varepsilon(\alpha(\alpha(\dot{=} , x), y)) &\longrightarrow x = y \\ \varepsilon(\dot{\top}) &\longrightarrow \top \\ \varepsilon(\dot{\perp}) &\longrightarrow \perp \\ \varepsilon(\alpha(\dot{\neg}, x)) &\longrightarrow \neg\varepsilon(x) \end{aligned}$$

etc. and identifying equivalent propositions is more natural than keeping these axioms as such, exactly like in the usual formulation of Simple Type Theory, β -normalizing terms and propositions is more natural than keeping β -conversion as an axiom. This idea has led to the development of *Deduction modulo*, that again was initially motivated by the will to express Simple Type Theory in it.

A third evolution is the introduction of binders in first-order predicate logic. Although this has been a hot topic recently, it is fair to say that we have not yet a completely satisfactory extension of first-order predicate logic with such binders.

To conclude, I want to mention the influence of Peter Andrews' work, course and book [4], on the emergence of the theoretical point of view on Simple Type Theory (although I do not attribute any point of view to anyone except myself). First, it is striking that in his course, Peter Andrews compared Simple Type Theory not only to first-order predicate logic but also to set theory in particular that he insisted on the fact that both theories are restriction of the naive, inconsistent, set theory with full comprehension. More technically, the alternative characterization of Henkin models, given by Peter Andrews [3] showed the way out of Henkin mysterious conditions that all λ -terms must have a denotation to a standard condition that the axioms S and K must be valid and thus to the idea that Henkin models were just models of some theory expressed in first-order predicate logic.

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