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Proving correctness of Algol-like programs in a formal system

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0. Introduction

In this paper, we shall introduce a formal system \mathcal{S} , in which we can prove the (partial) correctness of Algol-like programs. The method used to construct the system \mathcal{S} is essentially based on Hoare [2]. But in our system we can give a proof of the correctness of programs in a completely formal manner. Our system is a version of that in [4]. We shall compare the system \mathcal{S} with the inductive assertion method (see e.g. [3]), by using the infinitary language. We intend to construct \mathcal{S} rather for its formal properties than for its practical usefulness.

1. Formal system

Before introducing \mathcal{S} , we shall define the class of programs, called Algol-like programs.

Definition 1. Statements are defined inductively as follows.

- 1) An expression $y:=f(x_1, \dots, x_m)$ is a statement, where x_1, \dots, x_m and y are variables and f is an m -ary function symbol.
- 2) If S_1 and S_2 are statements and P is an n -ary predicate symbol, then if $P(x_1, \dots, x_n)$ then S_1 else S_2 is a statement.
- 3) If S is a statement and P is an n -ary predicate symbol, then while $P(x_1, \dots, x_n)$ do S is a statement.
- 4) If S_1, \dots, S_n ($n > 0$) are statements, then begin $S_1; S_2; \dots; S_n$ end is a statement.

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Any statement of the form of 4) is called an Algol-like program.

Formulas of the system \mathcal{S} are the same as those of the first order predicate calculus. We use $\neg, \wedge, \vee, \forall, \exists$ as logical connectives. A formula $A \supset B$ is considered as an abbreviation of the formula $\neg A \vee B$. $A_x[y]$ denotes the formula obtained from A by replacing each free occurrence of x in A by y . We assume that function symbols and predicate symbols appearing in the definition of statements are contained in the language of \mathcal{S} .

The system \mathcal{S} is a Gentzen-type one. We use the letters $\Gamma, \Gamma', \Delta, \Delta', \Theta, \Pi$ etc. to denote finite sets of formulas. $\Gamma_x[t]$ denotes the set of formulas which is obtained from Γ by replacing each free occurrence of x in every formula in Γ by a term t . Now, let S be a statement or empty and Δ is a nonempty set. Then $\Gamma \xrightarrow{S} \Delta$ is a sequent of \mathcal{S} . Informally, this expression means that if every formula in Γ holds, then every formula in Δ holds after the execution of the statement S terminates. Thus the above sequent is equivalent to the expression $A_1 \wedge \dots \wedge A_m \{ S \} B_1 \wedge \dots \wedge B_n$ in Hoare [2], where $\Gamma = \{A_1, \dots, A_m\}$ and $\Delta = \{B_1, \dots, B_n\}$. In particular, when S is empty, the above sequent has the same meaning as the sequent $\Gamma \rightarrow B_1 \wedge \dots \wedge B_n$ in Gentzen's LK [1]. Sometimes we write sets of formulas of the form $\Gamma \cup \{A\}$ and $\Gamma \cup \Gamma'$ as Γ, A and Γ, Γ' , respectively.

Any sequent of the form $\Gamma \rightarrow \Gamma$ is a beginning sequent of \mathcal{S} . Rules of inference of \mathcal{S} are as follows, where S is a statement or empty.

$$1) \frac{\Gamma \xrightarrow{S} \Delta}{\Gamma, \Gamma' \xrightarrow{S} \Delta}$$

$$2a) \frac{\Gamma \xrightarrow{S} \Delta \quad \Delta \longrightarrow \textcircled{H}}{\Gamma \xrightarrow{S} \textcircled{H}}$$

$$2b) \frac{\Gamma \longrightarrow \Delta \quad \Delta \xrightarrow{S} \textcircled{H}}{\Gamma \xrightarrow{S} \textcircled{H}}$$

$$3) \frac{\Gamma \longrightarrow A, \Delta}{\neg A, \Gamma \longrightarrow \textcircled{H}}$$

$$4) \frac{A, \Gamma \longrightarrow B}{\Gamma \longrightarrow \neg A \vee B}$$

$$5a) \frac{A, \Gamma \xrightarrow{S} \Delta}{A \wedge B, \Gamma \xrightarrow{S} \Delta}$$

$$5b) \frac{B, \Gamma \xrightarrow{S} \Delta}{A \wedge B, \Gamma \xrightarrow{S} \Delta}$$

$$6) \frac{\Gamma \xrightarrow{S} \Delta, A \quad \Gamma \xrightarrow{S} \Delta, B}{\Gamma \xrightarrow{S} \Delta, A \wedge B}$$

$$7a) \frac{\Gamma \xrightarrow{S} \Delta, A}{\Gamma \xrightarrow{S} \Delta, A \vee B}$$

$$7b) \frac{\Gamma \xrightarrow{S} \Delta, B}{\Gamma \xrightarrow{S} \Delta, A \vee B}$$

$$8) \frac{A, \Gamma \xrightarrow{S} \Delta \quad B, \Gamma \xrightarrow{S} \Delta}{A \vee B, \Gamma \xrightarrow{S} \Delta}$$

$$9) \frac{\Gamma \xrightarrow{S} A_x[y], \Delta}{\Gamma \xrightarrow{S} \forall x A, \Delta}$$

where y is a variable not appearing free in Γ and $\forall x A$, and neither x nor y appear in S .

$$10) \frac{\Gamma, A_x[t] \xrightarrow{S} \Delta}{\Gamma, \forall x A \xrightarrow{S} \Delta}$$

where t is a term.

$$11) \frac{\Gamma, A_x[y] \xrightarrow{S} \Delta}{\Gamma, \exists x A \xrightarrow{S} \Delta}$$

where y is a variable not appearing free in $\Gamma, \exists x A$ and Δ , and y is a variable not appearing in S .

$$12) \frac{\Gamma \xrightarrow{S} A_x[t], \Delta}{\Gamma \xrightarrow{S} \exists x A, \Delta}$$

where x is a variable not appearing in S and t is a term.

$$13) \frac{\Gamma \longrightarrow \Delta_y[f(x_1, \dots, x_m)]}{\Gamma \xrightarrow{y:=f(x_1, \dots, x_m)} \Delta}$$

$$14) \frac{A, \Gamma \xrightarrow{S_1} \Delta \quad \neg A, \Gamma \xrightarrow{S_2} \Delta}{\Gamma \xrightarrow{\text{if } A \text{ then } S_1 \text{ else } S_2} \Delta}$$

where A is of the form $P(x_1, \dots, x_n)$.

$$15) \frac{A, \Gamma \xrightarrow{S_1} \Gamma}{\Gamma \xrightarrow{\text{while } A \text{ do } S_1} \Gamma, \neg A}$$

where A is of the form $P(x_1, \dots, x_n)$.

$$16) \frac{\Gamma_0 \xrightarrow{S_1} \Gamma_1 \quad \Gamma_1 \xrightarrow{S_2} \Gamma_2 \quad \dots \quad \Gamma_{n-1} \xrightarrow{S_n} \Gamma_n}{\Gamma_0 \xrightarrow{\text{begin } S_1; S_2; \dots; S_n \text{ end}} \Gamma_n}$$

The notion of provability in \mathcal{S} is defined in the same way as LK.

Remark 2. Following two rules can be derived in \mathcal{S} .

$$i. \frac{\Gamma \xrightarrow{S} \Delta \quad \Gamma \xrightarrow{S} \Delta'}{\Gamma \xrightarrow{S} \Delta, \Delta'}$$

$$ii. \frac{\Gamma \longrightarrow \Delta, \Pi \quad \Pi, \Gamma' \longrightarrow \Delta'}{\Gamma, \Gamma' \longrightarrow \Delta, \Delta'}$$

Theorem 3. If the sequent $\Gamma \longrightarrow A_1, \dots, A_m$ is provable in LK, then the sequent $\Gamma \longrightarrow A_1 \vee \dots \vee A_m$ is provable in \mathcal{S} . (When $m = 0$, i.e., $\Gamma \longrightarrow$ is provable in LK, $\Gamma \longrightarrow B$ is provable in \mathcal{S} for any formula B.) Conversely, if $\Gamma \longrightarrow A_1, \dots, A_m$ is provable in \mathcal{S} then $\Gamma \longrightarrow A_1 \wedge \dots \wedge A_m$ is provable in LK.

In order to deal with a program on a particular domain, e.g.

a program on natural numbers, we need to define a theory on \mathcal{S} .

A theory T on LK is defined as a system obtained by adding some sequents of the form $\longrightarrow A$ to LK as beginning sequents. In this case, such a formula A is called an axiom of T. A theory $T(\mathcal{S})$ on \mathcal{S} is a system obtained from \mathcal{S} by adding a beginning sequent $\longrightarrow A$ for every axiom of a theory T (on LK). Theorem 3 holds also for T and $T(\mathcal{S})$.

Next, we shall consider the systems in which countably infinite conjunctions and disjunctions are admitted. So, in these systems

$\bigwedge_{j \in I} A_j$ and $\bigvee_{j \in I} A_j$ are formulas if I is at most countable.

Now, let LK^* and \mathcal{S}^* be the formal systems obtained from LK and \mathcal{S} , respectively, by changing the rules of inference concerned with conjunction and disjunction as follows. (For LK^* , S is empty in the following.)

$$\begin{array}{l}
 1a) \quad \frac{A_i, \Gamma \xrightarrow{S} \Delta \quad \text{for some } i \in I}{\bigwedge_{j \in I} A_j, \Gamma \xrightarrow{S} \Delta} \\
 1b) \quad \frac{\Gamma \xrightarrow{S} A_i, \Delta \quad \text{for any } i \in I}{\Gamma \xrightarrow{S} \bigwedge_{j \in I} A_j, \Delta} \\
 2a) \quad \frac{A_i, \Gamma \xrightarrow{S} \Delta \quad \text{for any } i \in I}{\bigvee_{j \in I} A_j, \Gamma \xrightarrow{S} \Delta} \\
 2b) \quad \frac{\Gamma \xrightarrow{S} A_i, \Delta \quad \text{for some } i \in I}{\Gamma \xrightarrow{S} \bigvee_{j \in I} A_j, \Delta}
 \end{array}$$

We can prove also that Theorem 3 holds for LK^* and \mathcal{S}^* .

2. Interpretation of \mathcal{S} in LK^*

In this section, we shall define an interpretation Φ of each sequent of \mathcal{S} . For each sequent $\Gamma \xrightarrow{S} \Delta$ of \mathcal{S} , a sequent $\Phi(\Gamma \xrightarrow{S} \Delta)$ of LK^* is defined so that $\Phi(\Gamma \xrightarrow{S} \Delta)$ is provable in LK^* if $\Gamma \xrightarrow{S} \Delta$ is provable in \mathcal{S} . Thus, we can say that every sequent provable in \mathcal{S} is 'true'. As shown in the following,

our interpretation has a close relation with the verification condition of the inductive assertion method.

Let S be a statement or empty. We define a formula $\mathcal{P}_S(A)$ of LK^* for each formula A of \mathcal{L} as follows.

$$1) \quad \mathcal{P}_S(A) \equiv A \quad \text{if } S \text{ is empty.}$$

$$2) \quad \mathcal{P}_S(A) \equiv A_y [f(x_1, \dots, x_m)] \quad \text{if } S \text{ is } y:=f(x_1, \dots, x_m).$$

$$3) \quad \mathcal{P}_S(A) \equiv (P(x_1, \dots, x_n) \wedge \mathcal{P}_{S_1}(A)) \vee (\neg P(x_1, \dots, x_n) \wedge \mathcal{P}_{S_2}(A))$$

if S is if $P(x_1, \dots, x_n)$ then S_1 else S_2 .

$$4) \quad \mathcal{P}_S(A) \equiv \bigwedge_{n=C}^{\infty} \sigma_n(A) \quad \text{if } S \text{ is } \underline{\text{while}} P(x_1, \dots, x_n) \underline{\text{do}} S_1,$$

where $\sigma_n(A)$ is defined by

$$\begin{cases} \sigma_0(A) \equiv \neg P(x_1, \dots, x_n) \supset A \\ \sigma_{n+1}(A) \equiv P(x_1, \dots, x_n) \supset \mathcal{P}_{S_1}(\sigma_n(A)). \end{cases}$$

$$5) \quad \mathcal{P}_S(A) \equiv \mathcal{P}_{S_1}(\mathcal{P}_{S_2}(\dots (\mathcal{P}_{S_n}(A)) \dots)) \quad \text{if } S \text{ is}$$

begin $S_1; S_2; \dots; S_n$ end.

Next, define Φ by

$$\Phi(\Gamma \xrightarrow{S} A_1, \dots, A_m) \equiv \Gamma \longrightarrow \bigwedge_{i=1}^m \mathcal{P}_S(A_i).$$

We can see that $\Phi(\Gamma \xrightarrow{S} \Delta)$ is the verification condition for the statement S .

Theorem 4. If a sequent $\Gamma \xrightarrow{S} \Delta$ is provable in \mathcal{L} , then

$$\Phi(\Gamma \xrightarrow{S} \Delta) \text{ is provable in } LK^*.$$

We don't know whether the converse of Theorem 4 holds. We can only show that when the statement S contains no while ... do ...-statements the converse holds, by using the cut-elimination theorem of LK^* . On the other hand, we have the following theorem.

Theorem 5. $\Phi(\Gamma \xrightarrow{S} \Delta)$ is provable in LK^* iff $\Gamma \xrightarrow{S} \Delta$ is provable in \mathcal{L}^* , where Γ and Δ are sets of formulas of LK^* .

The above theorem means that the system \mathcal{L}^* is 'complete'.

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