PROGRAM SCHEMAS WITH EQUALITY

BY

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Abstract

We discuss the class of program schemas augmented with equality tests, that is, tests of equality between terms.

In the first part of the paper we discuss and illustrate the "power" of equality tests. It turns out that the class of program schemas with equality is more powerful than the "maximal" classes of schemas suggested by other investigators.

In the second part of the paper we discuss the decision problems of program schemas with equality. It is shown for example that while the decision problems normally considered for schemas (such as halting, divergence, equivalence, isomorphism and freedom) are solvable for Iainov schemas, they all become unsolvable if general equality tests are added. We suggest, however, limited equality tests which can be added to certain subclasses of program schemas while preserving their solvable properties.

1. Introduction

In recent years the study of schemas has been widely pursued in an attempt to understand the power of programming languages. In the study of program schemas, the functions and predicates allowed are usually considered to be uninterpreted symbols. The reason for this is that very simple interpreted programs yield all the partial recursive functions, and therefore interpreted programs do not provide insight into the difficulty in programming; e.g., the difference between the essentially iterative nature of Fortran and the recursive structure of Algol or PL/1.

Earlier works in this area, e.g., Iainov [1960], Rutledge [1964], Paterson [1967, 1973] and Luckham, Park and Paterson [1970] essentially considered flowchart schemas, and emphasized the decision problems for schemas, viz. halting, divergence, equivalence, etc. Most of the recent papers, on the other hand, e.g., Paterson and Hewitt [1971], Strun [1971a], Constable and Grice [1971] and Garland and Luckham [1971] considered more powerful schemas, i.e., flowchart schemas with additional programming features like counters, recursion, push-down stacks and arrays; and were concerned mainly with the problem of translating program schemas from one class to another.

Several formalisms have been considered in the literature for the description of schemas.

We define a flowchart schema as being a program with the following features: it has a finite number of program variables denoted by \( Y_1, Y_2, \ldots \), a finite number of uninterpreted function symbols \( f_1, f_2, \ldots \) (which may be combined with the variables to form terms) and a finite number of predicate symbols denoted by \( P_1, P_2, \ldots \). Some of the function symbols may be zero-ary. These stand for individual constants, and are denoted by \( a_1, a_2, \ldots \). A statement in the program may be:

(a) an assignment statement of the form

\[
Y_i := t
\]

where \( t \) is any term,

(b) a predicate statement of the form

\[
\text{if } P(t_1, t_2, \ldots, t_n) \text{ then goto } L_1 \text{ else goto } L_2
\]

where \( t_1, \ldots, t_n \) are terms and \( L_1, L_2 \) are labels, or

(c) a terminal statement, i.e., a START statement, a HALT statement or a LOOP statement.

A schema has a unique START statement as its first statement. Free use of goto statements is allowed; and all statements except the START statement may be labelled. In addition, for convenience and readability we describe schemas using ALGOL-like features, e.g., while-statements and block structures. These clearly do not add any "power" and every such ALGOL-like program can be translated to an equivalent program that uses goto-statements instead.

Certain features can be added to flowchart schemas, e.g., counters or arrays. A counter is a special variable that takes nonnegative integer values. The operations allowed on a counter are adding one, subtracting one, and testing for zero. An array is a one-dimensional semi-infinite sequence of variables that can be referenced by using a counter to subscript the array.

In addition, we also consider recursive schemas. A recursive schema is a set of recursive definitions of functionals \( F_1, F_2, \ldots \) of the form

\[
P(t_1, t_2, \ldots, t_n) \quad \text{if } P(t_1, t_2, \ldots, t_n) \text{ then } t \text{ else } t'
\]

where \( r \) is an n-ary predicate symbol and \( t_1, t_2, \ldots, t_n \), \( t \) and \( t' \) are terms that may consist of function symbols, functionals and the variables \( Y_1, \ldots, Y_n \).
It is quite surprising, though, that people have so far neglected to mention one of the most useful features: equality tests between terms, i.e., statements of the form

\[
\text{if } t_1 = t_2 \text{ then goto } L_1 \text{ else goto } L_2 ,
\]

where \( t_1, t_2 \) are terms and \( L_1, L_2 \) are labels.

The extension of program schemas to allow equality is quite natural, much as is the extension of first order predicate calculus to first order predicate calculus with equality. The analogy can be extended further in that in both cases equality tests can be treated as just any other binary predicate but with a partial interpretation which in turn involves all other predicates and functions used in the system. This tends to be an unnatural approach to the treatment of equality. Accordingly, we prefer the direct approach of allowing the equality test to be a basic operation in the system as is the operation of assignment to a variable.

The reason for the omission of equality tests in earlier papers can perhaps be traced to the following fact. All schemas discussed in the papers mentioned above have one very important common property: the behavior of a schema for all interpretations can be characterized by the behavior for a subset of all interpretations, viz. the Herbrand interpretations. We therefore call all these schemas Herbrand schemas. To be somewhat more precise, in a Herbrand schema, for every interpretation there "corresponds" a Herbrand interpretation that follows exactly the same path of computation. Flowchart schemas with equality tests are in general non-Herbrand schemas, that is, they may behave quite differently for Herbrand and non-Herbrand interpretations. Consider, for example, the simple schema:

**START**

**if** a = b **then** HALT **else** LOOP.

The schema halts for some interpretations and loops for others. For all Herbrand interpretations, however, it always loops. It is therefore a non-Herbrand schema, and further, there can be no Herbrand schema that is equivalent to it. A non-Herbrand schema that has no equivalent Herbrand schema is said to be an inherently non-Herbrand schema.

The use of equality tests does not necessarily make a schema non-Herbrand. Example 0 in Appendix A is an interesting instance of a Herbrand program schema with equality tests that has an equivalent Herbrand program schema without any equality test and also an equivalent non-Herbrand program schema (which does have equality tests).

There are several other features which in general give rise to non-Herbrand schemas: the use of quantified tests is one such. Unfortunately, it is not partially decidable if a given schema is a Herbrand schema. This result follows from the fact that it is not partially decidable whether or not any given flowchart schema (without equality tests) diverges for every interpretation. Given any flowchart schema \( T \), replace every HALT statement by the statement

**if** a = b **then** HALT **else** LOOP,

where a is a new individual constant. Now the new schema is a Herbrand schema if and only if \( T \) diverges for every interpretation.

In the rest of this paper, we illustrate the power of equality tests (Section 2) and the decision problems concerning program schemas that use them (Section 3). For the sake of clarity we merely give the "flavor" of the examples in the main part of the paper, and we state the theorems without proof. Details of the examples are given in Appendix A (Section 4) and the proofs are sketched in Appendix B (Section 5). Detailed proofs can be found in Chandra [1972b].

2. The "Power" of Program Schemas with Equality

The use of equality tests in program schemas raises an old question that has been asked several times and never been answered to our complete satisfaction -- just what is a schema? We do not, in this paper, propose to answer this question, but we can indicate that much remains to be studied. It has been suggested (Constable and Gries [1972], Strong [1971]), for example, that the class of program schemas with array might be a "maximal" class of schemas, i.e., for every schema there exists an equivalent schema in this class. Now, it may be that the class of array-schemas is indeed maximal with respect to the Herbrand schemas, but nevertheless all schemas in this class are Herbrand schemas. It has been shown, however, that there exist certain schemas using equality tests that are inherently non-Herbrand. This means that the class of program schemas with arrays and equality tests is a strictly larger class.

A problem is said to be a Herbrand problem if it can be solved by a Herbrand Schema. A non-Herbrand problem is one that can only be solved by inherently non-Herbrand schemas. The class of program schemas with arrays and equality tests can solve certain non-Herbrand problems (which by the definition of a non-Herbrand problem cannot be solved if only arrays are allowed).

We first illustrate this point with two examples of non-Herbrand problems.

**Example 1:** Inverse of a unary function

Consider the following problem: "Given a unary function symbol \( f \), a finite number of other n-ary function symbols, \( n \geq 0 \), and an input variable \( x \), write a program schema that under any interpretation will yield a value of \( f^{-1}(x) \) as output. That is, it finds an element \( y \) that can be expressed in terms of the given function symbols and the input variable \( x \), such that \( f(y) = x \); if no such element exists, the schema loops forever". This problem, which is essentially one of inverting a given unary function, is non-Herbrand, the reason being that if the input \( x \) is equal to the zero-ary function \( a \) then it has no inverse in any Herbrand interpretation, whereas for other inputs \( y \) it may have an inverse. It follows that the task cannot be performed by any Herbrand schema.

The task is, however, well within the capability of flowchart schemas with arrays and equality tests. A schema in this class that solves this problem is described in Appendix A.

**Example 2:** Herbrand-like interpretations

Given a set of function and predicate symbols of which there is at least one zero-ary function,
we say that an interpretation $I$ for this set is Herbrand-like if there exists some Herbrand interpretation $H$ such that there is a 1-1 homomorphism from $H$ into $I$. In other words, an interpretation $I$ is Herbrand-like if and only if for every pair of distinct terms $t_1$ and $t_2$ (made up of the given functions) the elements in $I$ corresponding to $t_1$ and $t_2$ are distinct.

Now, consider the following problem: "given an interpretation for a set of function and predicate symbols, of which at least one is a zero-ary function, determine if the interpretation is not Herbrand-like. If the interpretation is not Herbrand-like then halt with no output, else diverge." This problem is inherently non-Herbrand in nature since a schema that solves this problem must diverge for every Herbrand interpretation. But for certain other interpretations the schema should halt. A schema with equality tests that solves the stated problem is presented in Appendix A.

The problem presented above is an abstract model closely related to certain problems in real life programming. As an illustration, consider a directed graph (with an identified root node) in which each node has two identified pointers leading from it. Pointers may lead to a terminal node "NIL". The problem is to determine whether or not the given graph is a tree. This problem may be modelled by the above problem with two monadic functions representing the two pointers, and with the difference that the search for the equality of two "terms" is conducted not for the entire set of all terms, but for those terms not representing NIL. The correspondence is that the interpretation is Herbrand-like for this set of terms if and only if the corresponding graph is a tree.

Another related problem is that of determining if a given list is circular. In this problem, too, the explicit use of equality in a schema model of the computation represents a more natural approach than the treatment of equality as an interpreted predicate.

While the main interest in equality tests stems from the fact that programmers frequently do use tests of equality between variables whose values are data elements and these tests are often of a non-Herbrand nature, equality tests find some interesting applications in problems that are really Herbrand in nature. We give two examples below.

Example 1: Translation of flowchart schemas with Counters

The recursive schema

$$F(x) = \text{if } p(x) \text{ then } F(F(f(x))) \text{ else } f(x)$$

can be translated to an "impure" flowchart schema by introducing a counter. It can also be translated to a rather horrendous flowchart schema without any explicit counter (Plaisted [1972]). However, the use of equality gives a relatively simple flowchart schema equivalent to the above while retaining the advantage of having a "pure" schema (all functions and predicates being left uninterpreted). Details are presented in Appendix A.

Example 4: Efficient translation of linear recursive schemas

Consider the recursive schema $T$:

$$F(a \text{ where } F(y) = \text{if } p(y) \text{ then } g(F(f(y)),y) \text{ else } y)$$

Let $I$ be an interpretation of $T$ for which there exists an $n$, $n \geq 0$, such that $I^n(a) = F^a(a) = \text{FALSE}$ and for all $k < n$, $I^k(a) = \text{TRUE}$. The output of the computation $(T,I)$ is the term

$$g(g(\ldots g(F^a(a),F^{a-1}(a))\ldots),F^a(a)),a).$$

For usual implementations of recursion the computation of the interpreted schema $(T,I)$ takes time (the number of operations on data structures performed) and space (the number of values stored) both proportional to $n$. The recursive schema $T$ can be translated to an equivalent flowchart schema using a fixed memory size (number of variables) and time proportional to $n^2$. Using equality tests, however, the time can be brought down to some constant times $\epsilon n^{1+\epsilon}$, where $\epsilon$ is any arbitrarily small positive number. Details of the construction are given in Appendix A. For further discussion of this topic, see Chandra [1972a].

3. Decision Problems

We consider the following decision problems for classes of schemas:

(a) The halting problem -- to decide whether a given schema in the class halts on every interpretation.

(b) The divergence problem -- to decide whether a given schema in the class diverges on every interpretation.

(c) The equivalence problem -- to decide whether two given schemas in the class are equivalent.

(d) The inclusion problem -- given two schemas $A$ and $B$ to decide whether $A$ includes $B$, i.e., for every interpretation either both schemas halt with the same output or schema $B$ diverges.

(e) The isomorphism problem -- to decide whether two schemas are isomorphic to each other. (Two schemas are said to be isomorphic, or operationally equivalent, if the sequences of statements executed by both schemas are exactly alike for every interpretation.)

(f) The freedom problem -- to decide whether a given schema in the class is free.

(g) The translation problem -- to translate any schema in the class to an equivalent free flowchart schema (using any number of variables).

It should be noted that the translation problem is not strictly a decision problem. We include it in this list, however, because it is an interesting problem closely related to the others.
All these questions can be answered in the affirmative for the class of lanov schemas which consists of one-variable flowchart schemas using only monadic function and predicate constants (lanov [1960], Rutledge [1964]). In view of this it is somewhat unexpected that the addition of general equality tests to lanov schemas renders all these decision problems unsolvable. On the other hand, we show that these problems for lanov schemas extended even to nonmonadic functions and resets but with limited equality tests are solvable.

It should be stated that for all "conventional" schemas, i.e., all schemas mentioned in this paper and in earlier works, the following problems are at least partially solvable:
(a) The halting problem -- to decide whether a given schema in the class halts on every interpretation.
(b) The non-divergence problem -- to decide whether a given schema ever halts,
(c) The non-isomorphism problem -- to decide if two schemas are not isomorphic to each other.
(d) The non-freedom problem -- given schema is not free.

The notable exceptions are the equivalence and inclusion problems. In general, the equivalence and inclusion problems as well as their negations are all not partially solvable.

3.1 Notation
We use the symbols
(1) $a, a_1, a_2, \ldots$ to represent individual constants (or zero-ary functions, if you will),
(2) $x, y, z, \ldots$ to represent program variables,
(3) $f, f_1, f_2, \ldots$ to represent functions, and we use
(4) $p, q, p_1, p_2, \ldots$ to represent predicates.

The set of terms is defined by the smallest set containing $a$'s, $x$'s and closed under the following operation: if $t_1, t_2, \ldots, t_n$ are terms, and $f_1$ is an n-ary function symbol, then $f_1(t_1, \ldots, t_n)$ is also a term.

We use the notation $t(y_1, y_2, \ldots, y_n)$ to represent that $y_1, y_2, \ldots, y_n$ are the only variables that may be present in $t$. Thus a term $t(y)$ may or may not contain the variable $y$, but contains no other variable. A term $t()$ indicates therefore a constant term, that is, a term that has no occurrences of $y$'s at all.

Given a nonconstant term $t(y)$, i.e., one containing the variable $y$, a common subterm $t'(y)$ of $t(y)$ is one such that if every occurrence of $t'(y)$ in $t(y)$ is replaced by an individual constant then $t(y)$ is reduced to a constant term. Clearly the terms $y$ itself and $t(y)$ are common subterms of $t(y)$. Also, if $t'(y)$ and $t''(y)$ are common subterms of $t(y)$ then $t'(y)$ is a common subterm of $t''(y)$ or vice versa.

The assignment depth $||t(y)||$ of a term $t(y)$ is defined to be the number of common subterms in $t(y)$ excluding $y$ itself. By convention, for a constant term $t()$, $||t()|| = 0$.

The depth $|t(y)|$ of a term $t(y)$ is the maximum depth of nesting in the term, and is defined by:

$$|t(y)| = 0,$$

$$|y| = 0,$$

$$|f(t_1, t_2, \ldots, t_n)| = \max(|t_1|, \ldots, |t_n|) + 1.$$

Note that for monadic terms $||t|| = |t|$, and in general $||t|| \leq |t|$. A few examples illustrate this point, in the following table

(a) stands for $t(y)$;
(b) stands for common subterms of $t(y)$ (excluding $y$ itself);
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(3) $f_1, f_2, \ldots$ to represent functions, and we use
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3.2 Solvable Classes
Consider the rather general class $S_1$ of flowchart schemas with one variable. Schemas in $S_1$ contain the following statement types ($L_1$ and $L_2$ are arbitrary labels in the definitions below):

START statement: $START y = a_1$

Final statements: $HALT$ or $LOOP$

Assignment statement: $y = t(y)$

Predicate-test st.: $if p(t_1(y), \ldots, t_n(y))$

Equality-test st.: $if t_1(y) = t_2(y)$

The equality tests allowed must, however, satisfy the condition that either $t_1(y)$ or $t_2(y)$ is a constant term, or else both $||t_1(y)||$ and $||t_2(y)||$ are less than or equal to 1.

THEOREM 1 (Solvability of $S_1$) . For the class $S_1$
1(a) the halting problem is solvable
1(b) the divergence problem is solvable
1(c) the equivalence problem is solvable
1(d) the inclusion problem is solvable
1(e) the isomorphism problem is solvable
1(f) the freedom problem is solvable
1(g) any schema can be effectively translated to an equivalent free schema (with the addition of extra program variables).

This theorem includes as special cases the results of Janov [1966], Judigue [1964], and also recent extensions by Kasell [private communication], and Garland and Luckham [1971].

As a special case, the problems (a)-(g) are solvable for the class of 1-variable monadic schemas allowing resets and equality tests of the forms:

\[ t_1(y) = t_2(y), \quad y = t_1(y), \quad y = f_1(y), \quad \text{and} \quad f_1(y) = f_2(y). \]

Consider, next, the class \( S_2 \) of schemas, similar to the class \( S_1 \), but with a change in the form of equality tests allowed, viz. the equality test statements allowed are of the form:

\[
\text{if } t_1(y) = t_2(y) \text{ then goto } L_1 \text{ else goto } L_2,
\]

but this time the restriction is that \( \|t_1(y)\| = \|t_2(y)\| \).

**THEOREM 2 (Solvability of \( S_2 \)):**

Problems (a)-(g) are solvable for the class \( S_2 \).

As a special case, the problems (a)-(g) are solvable for the class of 1-variable monadic schemas allowing resets and equality tests of the form:

\[ t_1(y) = t_2(y) \text{ where } |t_1(y)| = |t_2(y)|. \]

5.3 Unsolvable Classes

It should well be asked why we have the "strange" restrictions on the form of equality tests above. The answer is that even slight generalizations of the restrictions above yield, astonishingly, classes whose problems are unsolvable. We demonstrate this on two classes.

Consider the class \( S_3 \) consisting of one variable \( y \), one constant \( a \), no predicates and only monadic function constants. Statements in schemas of \( S_3 \) are of the forms:

\[
\text{START statement:} \quad \text{START}
\]
\[
\text{Final statements:} \quad \text{HALT or LOOP}
\]
\[
\text{Assignment statement:} \quad y = f_1(y)
\]
\[
\text{Equality-test st.:} \quad \text{if } f_1(y) = f_2(y) \text{ then goto } L_1 \text{ else goto } L_2.
\]

\( S_2 \) differs from \( S_1 \) in that nonconstant terms of depth 2 are used in equality tests; and it differs from \( S_2 \) in that terms tested for equality do not have the same assignment depth.

**THEOREM 3 (Unsolvability of \( S_2 \)):** For the class \( S_2 \):

3(a) the halting problem is unsolvable
3(b) the divergence problem is not partially solvable
3(c) the equivalence problem is not partially solvable
3(d) the inclusion problem is not partially solvable
3(e) the isomorphism problem is not partially solvable
3(f) the freedom problem is not partially solvable
3(g) there exists no effective translation to equivalent free schemas.

For the sake of completeness we should mention that the nonequivalence and the noninclusion problems for this class too are not partially solvable. Of course, the halting, nondivergence and nonisomorphism problems are partially solvable, which follows from the general result mentioned in the earlier parts of Section 5.

We introduce next the class \( S_4 \) of 1-variable monadic schemas similar to \( S_2 \) but with the difference that equality tests allowed have the following form:

\[
\text{if } y = t(y) \text{ then goto } L_1 \text{ else goto } L_2,
\]

where \( 1 \leq |t(y)| \leq 3 \), i.e., tests may have any of the forms:

\[ y = f_1(y), \quad y = f_1(f_2(y)), \text{ or } y = f_1(f_2(f_3(y))). \]

**THEOREM 4 (Unsolvability of \( S_4 \)):**

Problems (a)-(g) for the class \( S_4 \) are unsolvable.

A class of schemas is said to be solvable if its decision problems (a)-(c) are solvable; similarly, a class is unsolvable if its decision problems (a)-(e) are unsolvable. Classes \( S_1 \) and \( S_2 \) are solvable whereas \( S_3 \) and \( S_4 \) are unsolvable. On comparing these classes it is clear that there is a very sharp demarcation between classes of one-variable schemas that are solvable and those that are unsolvable, depending on the form of equality tests allowed. It should perhaps be asked how many function symbols suffice to render a class unsolvable. It can be shown, for example, that for the class \( S_3 \), merely 4 functions are sufficient.
It is more interesting to note, however, that these function symbols can be "coded" using only 2 function symbols so that schemas with one variable, two functions, and general equality tests, i.e., tests of the form \( t_1(y) = t_2(y) \), are unsolvable.

So far we have restricted our consideration to schemas with only one variable. The reason is obvious: one-variable schemas provide the most interesting solvable classes. When more variables are allowed, even a very few features tend to make the schemas unsolvable. For example, schemas with two variables, two functions, and tests only of the form \( y_1 = y_2 \) are unsolvable.

It is even more interesting, though probably not surprising, that schemas with a single function too are unsolvable; for example, the class of one-function schemas having tests only of the form \( y_1 = y_2 \) is unsolvable (5 variables suffice in this case).

The proofs of these secondary results are also presented in Appendix B.

Example 1: Inverse of a unary function

---

For simplicity we assume that the only functions are a single zero-ary function \( a \), the given unary function \( f \) and a binary function \( g \). The possible terms are therefore:

\[
\begin{align*}
x, & a, f(x), g(x,y), f(a), g(a,a), g(x,a), \\
g(a,x), f(f(x)), & \ldots
\end{align*}
\]

The schema for any other set of functions is similar to the one for this particular case.

Symbols \( c_1, c_2, c_3 \) stand for counters.

Strictly, the only operations allowed on counters are adding and subtracting one, and testing for zero. For convenience, however, we will also allow other statements such as \( c_1 = 0 \), \( c_2 = c_3 \), and tests like \( c_1 = c_2 \), as it is clear that these operations can be performed using only the legal operations and additional counters.

(1) -- START

\[
\begin{align*}
y_1 - y_2 & = a; \\
\text{L: if } p(y_1) \text{ then} & \\
& \text{if } p(y_2) \text{ then begin} \\
& \quad y_1 = f(y_1); \\
& \quad y_2 = f(y_2); \\
& \quad \text{goto L}; \\
& \text{end} \\
& \text{else if } y_1 = y_2 \text{ then HALT else LOOP} . \\
\end{align*}
\]

This is a Herbrand schema because the equality test \( y_1 = y_2 \) must always be true, and the equality test \( y_1 = a \) can never be entered. The given schema is hence equivalent to the following schema, which has no equality test.

(2) -- START

\[
\begin{align*}
y - a; \\
\text{L: if } p(y) \text{ then} & \\
& \text{if } y = f(y) \text{ then LOOP} \\
& \text{else begin} \\
& \quad y = f(y); \\
& \quad \text{goto L}; \\
& \text{end} \\
\text{else HALT} . \\
\end{align*}
\]

---

Example 0: A Herbrand schema with equality

Not all schemas that use equality tests are non-Herbrand. Consider, for example, the schema

(3) -- START

\[
\begin{align*}
y_1 - y_2 & = a; \\
\text{L: if } p(y_1) \text{ then} & \\
& \text{if } p(y_2) \text{ then begin} \\
& \quad y_1 = f(y_1); \\
& \quad y_2 = f(y_2); \\
& \quad \text{goto L}; \\
& \text{end} \\
& \text{else if } y_1 = a \text{ then HALT else LOOP} . \\
\end{align*}
\]

---

The following schema is also equivalent to the above schema, but it is a non-Herbrand schema because the LOOP statement in it can never be entered for any Herbrand interpretation. The schema is, however, not inherently non-Herbrand.

---

Example 1: Inverse of a unary function

After the initialization phase (lines (1) to (3))

\[
\begin{align*}
A[0] & = x, \quad A[1] = a, \quad c_1 = c, \quad c_2 = 1 .
\end{align*}
\]

After completing one pass through the outer loop of the program (lines (3) to (5))

\[
\begin{align*}
A[2] & = f(x), \quad A[3] = g(x,x), \quad c_1 = 1, \quad c_2 = 5 .
\end{align*}
\]

and after a second pass

\[
\begin{align*}
A[6] & = g(x,a), \quad A[7] = g(a,x), \quad c_1 = 2, \quad c_2 = 7 .
\end{align*}
\]
The algorithm works as follows: two pointers $c_1$ and $c_2$ reference the array. $A[c_1]$ represents the "current" value. If the current value is not the inverse, as determined by line (1), it is composed with values resulting in the enumeration by function applications, and the new values obtained are added to the array.

It can be shown by induction that the process of enumeration generates and tests each possible term exactly once. This means that the inverse will be found if it exists. The point at which the test of the inverse is made could be changed to effect time efficiency but without altering the main features of the program.

Example 2: Herbrand-like interpretations

We assume that the only functions are a single zero-ary function $a$, a unary function $f$ and a binary function $g$. Therefore the set of terms includes $a, f(a), g(a,a), f(f(a)), g(f(a),f(a)), g(a,f(a)), ...$

The required schema is:

(1) -- START
$A[0] = a;$
(2) -- $c_1 = c_2 = 0;$
(3) -- REPEAT:
$y = A[c_1];$
$\begin{array}{l}
\text{while } c_1 \neq 0 \text{ do} \\
\text{begin} \\
\text{if } A[c_1] = y \text{ then HALT; } \\
\text{end; } \\
\text{end; } \\
\text{c_2} = c_2 + 1; \text{A}[c_2] = f(y); \\
c_2 = c_2 + 1; \text{A}[c_2] = g(y,y); \\
c_2 = c_2 + 1; \text{A}[c_2] = g(y,f(a)); \\
\text{while } c_2 \neq 0 \text{ do} \\
\text{begin} \\
c_2 = c_2 + 1; \\
c_2 = c_2 + 1; \text{A}[c_2] = g(c_2,y); \\
c_2 = c_2 + 1; \text{A}[c_2] = g(y,c_2); \\
\text{end; } \\
c_1 = c_1 + 1; \\
\text{end; }
\end{array}$
(4) -- goto REPEAT.

This program is quite similar to the previous one in the manner of enumeration of terms. The fact that each term is generated exactly once is used in making the test (4) to check if a value is repeated.

Example 3: Translation of flowchart schemas with Counters

The recursive schema
$F(a)$ where
$F(y) = \text{if } p(y) \text{ then } f(y(f(y))) \text{ else } f(y),$

can be translated to a flowchart schema with one program variable $y$ and one counter $c$.

START
$y = a;$
(1) -- $c = 0;$
while true do
\begin{array}{l}
\text{if } p(y) \text{ then } \\
y = f(y); \text{c} = c + 1; \text{end; } \\
\text{else begin } \\
y = f(y); \text{c} = c + 1; \text{end; } \\
\text{if } c = 0 \text{ then goto DONE; } \\
\text{c} = c - 1; \text{end; } \\
\text{DONE: HALT(y);} \\
\end{array}$

Note that the test " $c = 0 "$ above is not a test of equality between two data structures but rather between an interpreted variable, i.e., $c$, and an interpreted constant, i.e., 0.

The corresponding equivalent flowchart schema with equality tests instead of counters uses three variables:

$y$ plays the same role as the variable $y$ above, $z$ effectively simulates a counter, and $w$ is a temporary variable.

The idea behind the method is that the variable $z$ simulates a counter, where $f'(a)$ stands for the integer 1. Therefore, the statement $c = 0$ stands for the statement $c = 0$, $z = f'(a)$ stands for $c = c - 1$, and the statements $\{v = a; \text{while } f(w) \neq z \text{ do } w = f(w); z = v \}$ stand for $c = c - 1$. We have to be careful, however.

The term $f'(a)$ stands for the integer $n$, $n \geq 0$, only if for no two distinct numbers $i, j \leq n$ are the terms $f'(a)$ and $f'(a)$ equal. Interpretations for which the counter is required to count up to an integer $n$ where there exist $i, j \leq n$, $i \neq j$, such that $f'(a) = f'(a)$ are called looping interpretations. It can be shown that for looping interpretations the given recursive schema never halts. The required program schema is therefore easy to construct:

\begin{array}{l}
\text{START } \text{REPEAT } \\
y = a; \text{c} = 0; \text{while true do } \\
\text{if } p(y) \text{ then } \\
y = f(y); \text{c} = c + 1; \text{end; } \\
\text{else begin } \\
y = f(y); \text{c} = c + 1; \text{end; } \\
\text{if } c = 0 \text{ then goto DONE; } \\
\text{c} = c - 1; \text{end; } \\
\text{DONE: HALT(y);} \\
\end{array}$
Example 4: Efficient translation of linear recursive schemes.

Consider the recursive schema $T$:

$$F(a)$$

where

$$F(y) = \begin{cases} \text{if } p(y) \text{ then } c(F(f(y)), y) & \text{else } y \end{cases}$$

Let $I$ be an interpretation of $T$ for which there exists an $n > 0$, such that $r^n(a) = \text{FALSE}$, and $r^k(a) = \text{TRUE}$ for all $k < n$.

The output of the computation of $(T, I)$ is

$$c(a, \ldots, c(r^n(a), r^{n-1}(a), \ldots, r^2(a), r(a), a) \ldots)$$

The computation of $(T, I)$ takes time and space proportional to $n^2$, for usual implementations of recursion. The recursive schema can be translated to an equivalent flowchart schema $T'$ using a fixed memory size (number of variables) such that the computation of $(T', I)$ takes time proportional to $n^2$, as follows:

**START**

1. $y = a$;
2. while $p(y)$ do $y = f(y)$;
3. end;
4. $x = f(a)$;

**DONE:** $\text{HALT}(a)$.

Using equality tests, however, the time can be brought down to $n^{1+\varepsilon}$, where $\varepsilon$ is an arbitrarily small number. We first describe an equivalent flowchart schema with equality tests with a $\varepsilon$ time bound of $n^{3/2}$.

Intuitively, the idea is the following. The earlier flowchart schema spends most of its time trying to find the inverse of the function $f$ (i.e., given $f^n(a)$, to find $f^{-n}(a)$) -- though this operation is somewhat hidden in the program. We can speed up this by planting a value at a "distance" of about $n$ from the end and compute inverses from this planted value. Time taken to find the square root is of the order of $n^{1/2}$, average time to find the inverse is $n^{1/2}$ (done $n$ times) and time to reset the planted value is of the order of $n$ (done $n/2$ times). In general, by planting $(k-1)$ values (instead of just one) at distances

$$n^{1/k}, n^{2/k}, n^{3/k}, \ldots, n^{(k-1)/k}$$

from the end we get a time bound of $n^{1+1/k}$.

**START**

1. $y = a$;
2. while $p(y)$ do $y = f(y)$;
3. if $y = a$ then $\text{HALT}(a)$;
4. end;

**DONE:** $\text{HALT}(a)$.

Using equality tests, however, the time can be brought down to $n^{1+\varepsilon}$, where $\varepsilon$ is an arbitrarily small number. We first describe an equivalent flowchart schema with equality tests with a $\varepsilon$ time bound of $n^{3/2}$.

Intuitively, the idea is the following. The earlier flowchart schema spends most of its time trying to find the inverse of the function $f$ (i.e., given $f^n(a)$, to find $f^{-n}(a)$) -- though this operation is somewhat hidden in the program. We can speed up this by planting a value at a "distance" of about $n$ from the end and compute inverses from this planted value. Time taken to find the square root is of the order of $n^{1/2}$, average time to find the inverse is $n^{1/2}$ (done $n$ times) and time to reset the planted value is of the order of $n$ (done $n/2$ times). In general, by planting $(k-1)$ values (instead of just one) at distances

$$n^{1/k}, n^{2/k}, n^{3/k}, \ldots, n^{(k-1)/k}$$

from the end we get a time bound of $n^{1+1/k}$.
(1) -- while \( z \neq x_1 \) do
  begin
    \( s_j \leftarrow s_j \);
    while \( f(s_j) \neq z \) do \( x_j \leftarrow f(s_j) \);
    \( y \leftarrow c(x_j) \);
    \( z \leftarrow x_j \);
  end;

(2) --
  TEST: if \( z = a \) then HALT(y);

(3) -- \( x_2 \leftarrow a \); while \( (x_2 \neq z) \) and \( (x_2 \neq x) \) do \( x_2 \leftarrow f(x_2) \);
  goto REPEAT.

Line (1) detects if there exists an \( n \geq 0 \) such that \( r^a(a) = \text{FALSE} \) and \( r^a(a) = \text{TRUE} \) for all \( k < n \). If such an \( n \) does not exist the program loops forever which is the desired operation. If \( n \) exists it follows that for all \( i,j \leq n \), if \( i \neq j \) then \( r^i(a) \neq r^j(a) \). At this point \( y = r^a(a) \).

If \( n = 0 \) the program halts with output \( a \) (line 2). If \( n = 1 \) the CHECK loop segment of the program from lines (3) to (4) finds the smallest positive integer \( m \) such that \( m \times n \geq n \). This is done by successively trying larger and larger values \( i = 1,2,3,\ldots \) for \( m \) until one is found such that \( i \times n \geq n \). This is the required value for \( m \). We use the variable \( x \) to store the value of \( r^i(a) \) and the variable \( y \) to "count" up to \( i \times n \) by successively taking values \( a,f(a),\ldots,f^i(a) \). The final value of \( x \) is \( r^a(a) \) and it remains unchanged for the rest of the program.

Execution of lines (5) to (9) now causes the variable \( x_1 \) to be "planted" at \( r^{m-1}(x) \). The while statement between lines (7) and (8) constitutes the main part of the program. The variable \( y \) takes on values in the sequence

\[
r^a(a), \quad c(r^a(a),r^{a-1}(a)), \quad c(c(r^a(a),r^{a-2}(a)),r^{a-2}(a)), \quad \ldots
\]

On exit from this while-loop the value of \( z \) is \( r^{m-1}(a) \).

Liners (9) and (5) to (9) are then used to reset the planted value to \( r^{m-1}(a) \) and the process is repeated. After it, the planted value is reset to \( r^{m-2}(a) \), and so on. A special case is encountered when the integer corresponding to \( z \) becomes less than \( m \). In this case, the next planted value should be simply \( a \), and hence the use of line (10) instead of simply setting \( x_2 = x \).

5. Appendix B — Proof of Theorem 1

We use the terminology \( T_1 \supseteq T_2 \) to mean the schemas \( T_1 \) and \( T_2 \) are equivalent, and \( T_1 \supset T_2 \) to mean \( T_1 \) includes \( T_2 \).

Proof of Theorem 1 (Solvability of \( S_i \))

1(a), (b), (c): The solvability of the halting, divergence and equivalence problems follows from the solvability of inclusion:

(a) Given a schema \( T \) for \( S_i \), \( T \) halts if and only if \( T \supseteq H \) where \( H \) represents the schema \([\text{START}; \text{HALT}(a)]\) that always halts with output \( a \), and \( T \) is the schema \( T \) with all \( \text{HALT} \) statements changed to \( \text{HALT}(a) \).

(b) Given a schema \( T \) for \( S_i \), \( T \) diverges if and only if \( L \supset T \), where \( L \) represents the schema \([\text{START}; \text{LOOP}]\) that always loops.

(c) Given two schemas \( T_1 \) and \( T_2 \) of \( S_i \), \( T_1 \supseteq T_2 \) if and only if \( T_1 \supset T_2 \) and \( T_2 \supset T_1 \).

1(d): We give below only the intuitive idea behind the proof of solvability of the inclusion problem. Given two schemas \( T_1 \) and \( T_2 \) of \( S_i \), to decide if \( T_1 \supset T_2 \), an automaton is constructed that simulates the computations of \( T_1 \) and \( T_2 \) in parallel. The input tape of the automaton represents an interpretation for \( T_1 \) and \( T_2 \). The input tape is rejected if both \( T_1 \) and \( T_2 \) halt but with different outputs, or if \( T_2 \) halts and \( T_1 \) diverges, under the interpretation corresponding to the input tape; otherwise, the tape is accepted.

To describe the operation of the automaton we first introduce the notion of the "specification state" of a variable \( y \). The specification state represents the outcomes of all possible tests that could be performed by a schema without changing the value of the variable \( y \) (and using terms no "larger" than the "largest" term used in the schemas \( T_1 \) and \( T_2 \)). The automaton simulates the computations of \( T_1 \) and \( T_2 \) not just for the main-line computation, but for a large number of "instances" of the variable \( y \). There is one instance for each assignment statement and each constant term (no larger than the largest term). The computation of an instance (for an assignment statement and a term) represents what the schema would really do if the main-line variable happened to equal that constant term after that assignment statement.

The computation on each instance is kept in step, and the automaton keeps track of which instances have equal values at each step. This enables the automaton to detect whether the input tape really represents a feasible interpretation.

The reason that this specification state approach works with limited equality tests is that the finite specification state carries sufficient information to allow it to be updated. This is not true for general equality tests, e.g., in the
classes $S_2$ and $S_4$, if a specification state were to carry all information necessary to update it, the amount of information would grow without bound as the computation proceeded.

Proof of Theorem 1 (Unsolvability of $S_2$)

(i): The proof of isomorphism is similar to the proof of inclusion, except that the automaton not only keeps track of which instances are equal in value at each step, but also which equal instances have an isomorphic history. The automaton can then detect if for any input tape the computations of the two schemas are not isomorphic.

(ii): Freedom or nonfreedom is detected by the algorithm $I(g)$ that translates a given schema in $S_1$ to an equivalent free schema; if ever a test statement is detected for which some exit is not feasible the schema is not free, else it is free.

(iii): We give below a short outline for the translation of a given schema $T$ in $S_1$ to an equivalent free schema $T_1$ (using several variables).

A "partial specification state" is like a specification state but with the possibility that the values of certain predicate and equality tests may be unknown. The schema $T_1$ has a (large) number of variables, one variable for each assign-ment statement and each constant term (no larger than the largest term used in $T$).

The schema $T_1$ begins by assigning all variables their corresponding initial values. The schema $T_1$ has a (large) number of "chunks" of statements. Each chunk updates the variables. This corresponds to one step of the automaton in the proof of inclusion. This updating can be performed without introducing any nonfreedom. Each chunk is associated with the following information (line (ii) is unnecessary for this problem, but it is required to solve the freedom problem).

(i) The statement in $T$ corresponding to each variable in $T_1$.

(ii) Which variables have equal values.

(iii) Which pairs of variables have the property that they both have tested the same value if we hadn't explicitly avoided that (i.e., if both variables are "entered" by the main-line computation, nonfreedom would result).

When updating is performed, no predicate or equality test is introduced whose outcome is known from the information corresponding to the chunk. Loops are detected as before; and some variables may become "inactive" either by looping or halting.

Proof of Theorem 2 (Solvability of $S_2$)

The proof of Theorem 2 is similar to the proof of Theorem 1 except that the formal definition of the specification state reflects the different kind of equality tests allowed.

Proof of Theorem 2 (Unsolvability of $S_4$)

We define a class $S_5$ of schemas having two variables $y_1$ and $y_2$, and whose statements consist of the following:

Start statement: START $y_1 - y_2 - a$;

Final statements: HALT or LOOP

Test statement: $y = f(y_1)$;

if $p(y_1)$ then goto $L_4$

else goto $L_5$;

It was shown by Luckham, Park and Peterson (1970) that the halting problem for the class $S_5$ is unsolvable, and that the divergence problem is not partially solvable.

To show the halting problem for $S_5$ to be unsolvable we reduce the halting problem for $S_5$ to that for $S_1$; that is, we describe an algorithm that takes any schema $T_5$ in the class $S_5$ as input and yields a schema $T_1'$ in the class $S_1$ such that $T_1'$ halts if and only if $T_5$ halts.

Similarly, to show that the divergence problem for $S_5$ is not partially solvable we describe an algorithm that takes $T_5$ as input and yields as output a schema $T_1''$ in the class $S_1$ such that $T_1''$ diverges if and only if $T_5$ diverges. We will unify the construction for the two cases by constructing for both cases a schema $T_1$ in the class $S_1$ but augmented with a special final statement called the "REJECT" statement:

REJECT statement: REJECT.

The REJECT statement signifies that the interpretation is unacceptable and is rejected. Loosely the idea is the following. There exists a map from interpretations of $T_5$ that are not rejected onto the interpretations of $T_1$ such that the computation for $T_1$ under an interpretation halts if and only if the computation for $T_5$ under the corresponding interpretation halts.

Now it is clear that if we replace all REJECT statements in $T_1$ by HALT statements to get $T_1''$, then $T_1''$ halts on every interpretation if and only if $T_5$ halts on every interpretation. Similarly, if we replace all REJECT statements by LOOP statements to get $T_1'$ then $T_1'$ diverges on every interpretation if and only if $T_5$ diverges on every interpretation.

Given a schema $T_5$ in $S_5$, we construct the corresponding schema $T_1$ in $S_1$ (with the addition of REJECT statements) as follows. We use the
variable $y$ of $T_j$ to represent the latest variable tested in $T_j$, i.e., $y_1$ or $y_2$. The function $f$ plays the same role in $T_j$ as in $T_i$. The schema $T_j$ simulates a computation of $T_j$ as follows. In the diagram below the elements $a, f(a), f(f(a))$ are represented by contiguous squares from left to right. We superimpose on this diagram the computations of both $T_j$ and $T_i$. Suppose, at some instant in the computation of $T_j$, $y_1$ is at point $A$, and $y_2$ is at $C$, and suppose $y_1$ is being "read". $T_j$ makes certain that the $f_2$ pointers from the squares scanned point to the right of $y_1$. Suppose that we continue to "read" from $y_1$ until $y_1$ reaches point $B$ where the schema $T_j$ starts "reading" from $y_2$. $T_j$ checks that the $f_1$ pointers from the squares scanned point to the right of $B$.

We are now in a position to describe the construction of $T_j$. Without loss of generality, we will assume that in $T_j$, the first test statement tests the variable $y_1$. $T_j$ will effectively contain 2 copies of $T_i$ except there is only one start statement. We will call these copies $A$ and $B$. We will label statements of $T_j$ by numbers $1, 2, 3, \ldots$. The corresponding statements in $T_j$ will be labelled $1-A$, $1-B$, $2-A$, $2-B$, $3-A$, $3-B$, $\ldots$.

(i) The start statement in $T_j$ is

```
START
y_1 \rightarrow y_2
```

The corresponding statements in $T_j$ are:

```
START
y_1 \rightarrow y_2
```

Note that the test $f(y) \neq f_2(y)$ is not strictly an allowed statement. We use this form for clarity: it can really be "simulated" by the statements:

```
if f(y) < f_2(y) then REJECT;
else goto i-A;
```

(ii) For any test statement $i$ in $T_j$, if $i$ is of the form:

```
if p(y) then goto i; else goto k;
```

the corresponding statements $i$-A and $i$-B are:

```
i-A: if f_1(y) \neq f_2(f(y)) then REJECT;
else goto j-A;
i-B: if f_2(y) \neq f_1(f(y)) then REJECT;
else goto j-B;
```

(iii) For any test statement $i$ in $T_j$ of the form:

```
i: y_2 \rightarrow y_1
```

the corresponding statements $i$-A and $i$-B are similar to the above, except, one has to interchange $f_1$ with $f_2$ and $A$ with $B$.

(iv) WHILE and LOOP statements remain unchanged.

This completes the construction.
The main reason that the schema $T_5$ can simulate the computation of $T_2$ is that each $T_1$, in the "pointer" is checked at most once from each square. If pointers were to be checked twice and it turned out that they were required to point to different values, there might exist no interpretation satisfying this condition -- the result would be that all interpretations of $T_5$ would be rejected.

\( \text{(g)} \): The non-partial solvability of the equivalence problem follows directly from the non-partial solvability of the divergence problem (Part (b)), since a program schema in $S_2$ diverges if and only if it is equivalent to the schema:

\[
\begin{align*}
\text{START} & \quad y = a; \\
\text{LOOP} & \quad y = a;
\end{align*}
\]

Then $T$ and $T'$ are isomorphic if and only if $T$ diverges.

\( \text{(f)} \): The non-partial solvability of the inclusion problem follows directly from the non-partial solvability of the equivalence problem since $T_1 \subseteq T_2$ if and only if $T_1 \supseteq T_2$ and $T_2 \supseteq T_1$.

\( \text{(e)} \): The non-partial solvability of the isomorphism problem also follows directly from the non-partial solvability of the equivalence problem. Given a schema $T$ in the class $S_4$, construct a new schema $T'$ also in $S_4$ obtained by replacing each HALT statement in $S_2$ by the statements:

\[
y = f(y); \\
\text{HALT}.
\]

Proof of Theorem 4 (Unsolvability of $S_4$)

The proof goes along lines quite similar to the proof for Theorem 3. We first define a subset $S_4'$ of the class of schemas $S_4$. $S_4'$, like $S_5$, has two variables $y_1$ and $y_2$, one function symbol $f$, and one predicate symbol $p$. However, $S_4'$ has the constraint that in any path through a schema of $S_4'$, after each statement that tests the variable $y_1$ there must be either one or two statements that test $y_2$ (followed by a final statement or another test of $y_1$) -- note the form of the test statement of $S_4$ defined in the proof of $S_4$'s (b). The halting and divergence problems of $S_4'$ can be shown to be unsolvable, and the halting and divergence problems of $S_4'$ can be reduced to those of $S_4$. This implies the unsolvability of problems (a)-(e) and (g) for $S_4$. The freedom problem (f) can be shown to be unsolvable on lines similar to the proof for $S_4$, i.e., by reducing PCP to the non-freedom problem and effectively simulating two variables while actually using only one.

Proofs of Secondary Results

In the following results the number of functions does not include the individual constants.

1. Schemas with One Variable, Two Functions and General Equality Tests

The class of flowchart schemas with one variable, two functions (no predicate) and general equality tests is unsolvable.

If completely general equality tests are allowed it is easy to see that two function constants suffice to render the class of schemas unsolvable because more function letters can be "coded" in terms of two functions. For example, in $S_2$ we could use only two functions $f$ and $g$ by making in the construction of $T_3$ from $T_5$ the following substitutions: for all terms $t$ simultaneously substitute:

\[
f(f(t)) \quad \text{for} \quad f(t) \\
g(t) \quad \text{for} \quad f(t) \\
g(f(t)) \quad \text{for} \quad f(t) \\
f(t) \quad \text{for} \quad f(t) \\
g(t) \quad \text{for} \quad f(t)
\]

All the unsolvability results go through on making this substitution. Similar substitutions can be made to show the unsolvability of freedom.

2. Schemas with Two Variables, Two Functions and Restricted Equality Tests

The class of flowchart schemas with two variables and two functions (no predicate) with tests only of the form $y_1 = f(y_2)$ are unsolvable.

Consider the class $S_7$, which is the same as $S_5$, but with the difference that there are two function constants $f_1$ and $f_2$, and no predicate constant.

The computation of any schema $T_2$ in $S_2$ can be simulated by a corresponding schema $T_7$ in $S_7$, obtained by replacing every test statement of the form $y_1 = f(y_2)$ by a test statement of the form $y_1 = f_1(y_1)$.

\[
\text{if } p(y_1) \text{ then goto } L_1 \text{ else goto } L_k
\]

by a test statement of the form $y_1 = f(y_1)$.

\[
\text{if } y_1 = f_2(y_1) \text{ then goto } L_1 \text{ else goto } L_k
\]

The proof goes along lines quite similar to the proof for Theorem 4. We first define a subset $S_4'$ of the class of schemas $S_4$. $S_4'$, like $S_5$, has two variables $y_1$ and $y_2$, one function symbol $f$, and one predicate symbol $p$. However, $S_4'$ has the constraint that in any path through a schema of $S_4'$, after each statement that tests the variable $y_1$ there must be either one or two
it is easy to see that for any path, finite or infinite, through \( T \), if there exists an interpretation for which \( T \) executes statements along this path, then there is an interpretation for which \( T \) executes statements along the corresponding path. Thus this establishes the unsolvability of (a)-(c) and (d) for the class \( \mathcal{D} \), (note that the unsolvability of (a)-(c) and (d) follows from the unsolvability of (b)).

Furthermore, the freedom problem too can be shown to be unsolvable by reducing FCP to it. The reduction is related to the corresponding reduction in Paterson [1967], but it is not so clear that it is the case that we need the additional "cleverness" of padding each symbol of the FCP with enough "bits" in order to allow for testing, to effect a non-deterministic search.

(iii) Schemes with One Function, Restricted Equality Tests

Schemes with one function using tests only of the form \( T_i = T_j \) are unsolvable.

The halting and divergence problems for two-counter automata are known to be unsolvable (Hopcroft and Ullman [1969]), and can be reduced to the halting and divergence problems for one-function schemas in a rather direct manner. In the reduction process the only care that has to be taken is for the operation of incrementing one to a counter, in which case the schema checks for a looping interpretation as in Example 3 of Appendix A. The unsolvability of the equivalence, inclusion, and isomorphism problems follows from the unsolvability of the halting and divergence problems.

6. References


