

# **An approach for the understanding of scientific application programs based on program specialization**

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## **Abstract**

This paper reports on an approach for improving the understanding of old programs which have become very complex due to numerous extensions. We have adapted partial evaluation techniques for program understanding. These techniques mainly use propagation through statements and simplifications of statements. We focus here on the automatic interprocedural analysis and we specify both tasks for call-statements, in terms of inference rules with notations taken from the specification languages B and VDM. We describe how we have implemented in a tool, and used that interprocedural analysis to improve program understanding. The difficulty of that analysis is due to the lack of well defined interprocedural mechanisms and the complexity of visibility rules in Fortran.

**Keywords:** software maintenance of legacy code, program understanding, program specialization, interprocedural analysis, inference rules, natural semantics, formal specification, Fortran.

## 1 Introduction

Older software systems are inherently difficult to understand (and to maintain). Much of the effort involved in software maintenance is in locating the relevant code fragments that implement the concepts of the application domain. The maintainer is often faced with the problem of locating specific program features or functionalities within a large and partially understood system [15].

First, there exists now a wide range of tools to support program understanding [13]. Either they transform programs given a criteria (for instance they restructure programs) or they represent programs according to various formalisms (for instance graphic formalisms showing data and control flows). Hierarchies constructed by these tools should reflect semantics and not just pleasing graph layouts [12]. Program understanding involves recognizing meaningful entities and their dependencies: calling relationships between subroutines, data flow relationships between variables, definition relationships between variables and types. They are important for understanding the code, but many of their code is difficult to find because it is often fairly deeply embedded within the program.

Next, such tools are fully automated and not customizable. But, there will always be users who will want something else. No tool can foresee all the situations a user will encounter; customizations, extensions and new applications inevitably become necessary. Thus, instead of supporting a non flexible builder-oriented approach, a program understanding tool should support diverse user tastes and preferences as the users' view of the code.

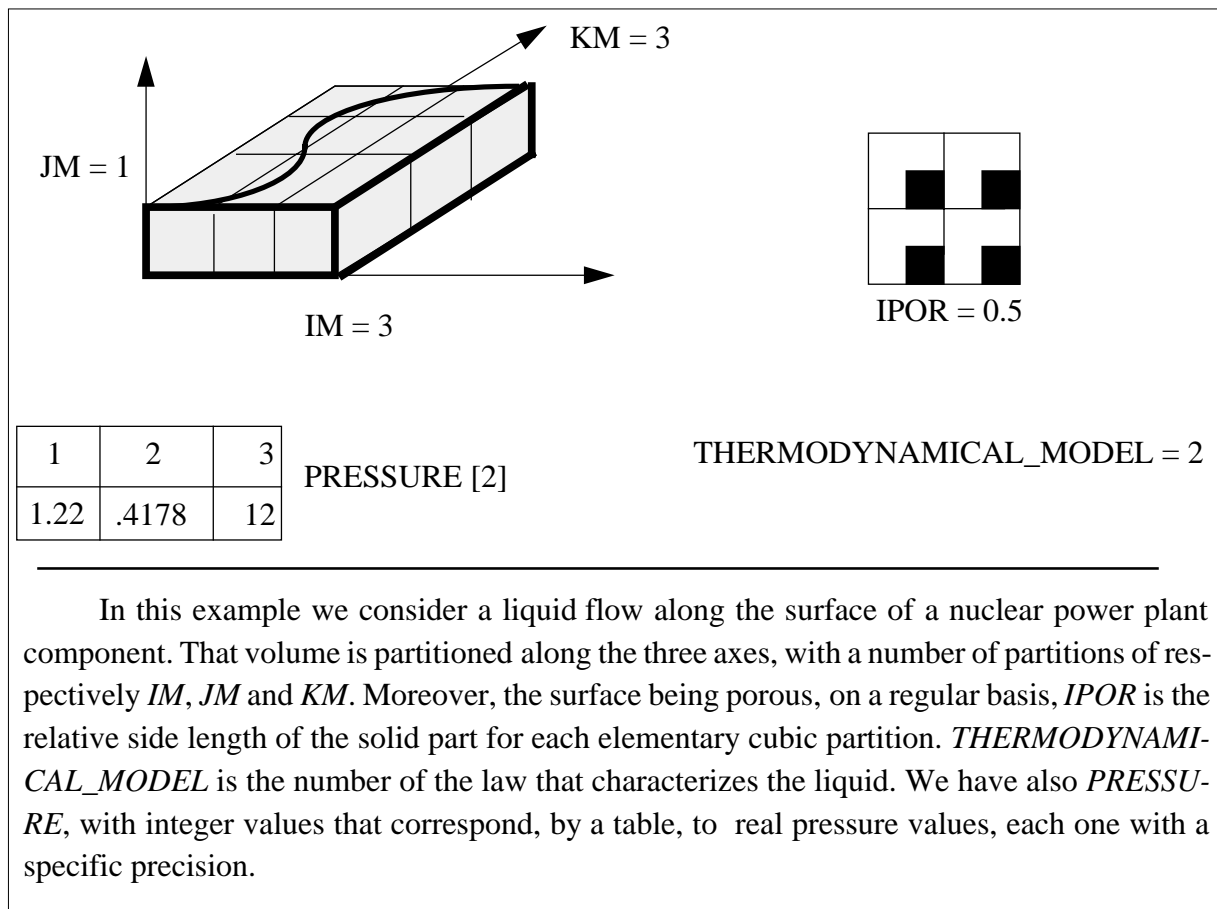
Last, most market tools apply to whole programs or files. They do not gather all pertinent information to the user. For every large system, the information generated by a tool is often prodigious. Presenting the user with reams of data is insufficient. Only the knowledge of this data is important for the user. In a sense, a key to program understanding is deciding what to look and what to ignore.

Scientific programming is a good example that shows the difficulties of the program understanding task. Many scientific application programs, written in Fortran for decades, are still vital in various domains (management of nuclear power plants, of telecommunication satellites, etc.), even though more modern languages are used to implement their user interfaces. It is not unusual to spend several months to understand such application programs before being able to maintain them. For example, understanding an application program of 120,000 lines of Fortran code took nine months. So, providing the maintainer with a tool, which finds parts of lost code semantics, allows to reduce this period of adaptation.

Such observations in an industrial context ([7]) led us to develop a software maintenance tool to help in understanding scientific application programs. The peculiarities of our tool are the following:

- the tool is adapted to scientific application programs. In such programs, the technological level of scientific knowledge (linear systems resolution, turbulence simulation, etc.) is higher than the knowledge usually necessary for data processing (memory allocation, data representations). The discrepancy is increased by the widespread use of Fortran, which is an old-fashioned language. Furthermore, for large scientific applications, Fortran 77 [6], which

is quite an old version of the language, is used exclusively to guarantee the portability of the applications between different machines (mainframes, workstations, vector computers). Furthermore, scientific application programs we have studied have been developed a decade ago. During their evolution, they had to be reusable in new various contexts. For example, the same thermohydraulic code implements both general design surveys for a nuclear power plant component (core, reactor, steam generator, etc.) and subsequent improvements in electricity production models. The result of this encapsulation of several models in a single large application domain increases program complexity, and thus amplifies the lack of structures in the Fortran programming language. This generality is implemented by Fortran input variables whose value does not vary in the context of the given application. We distinguish in [4] two classes of such variables and we give in Fig.1 an example of such variables.



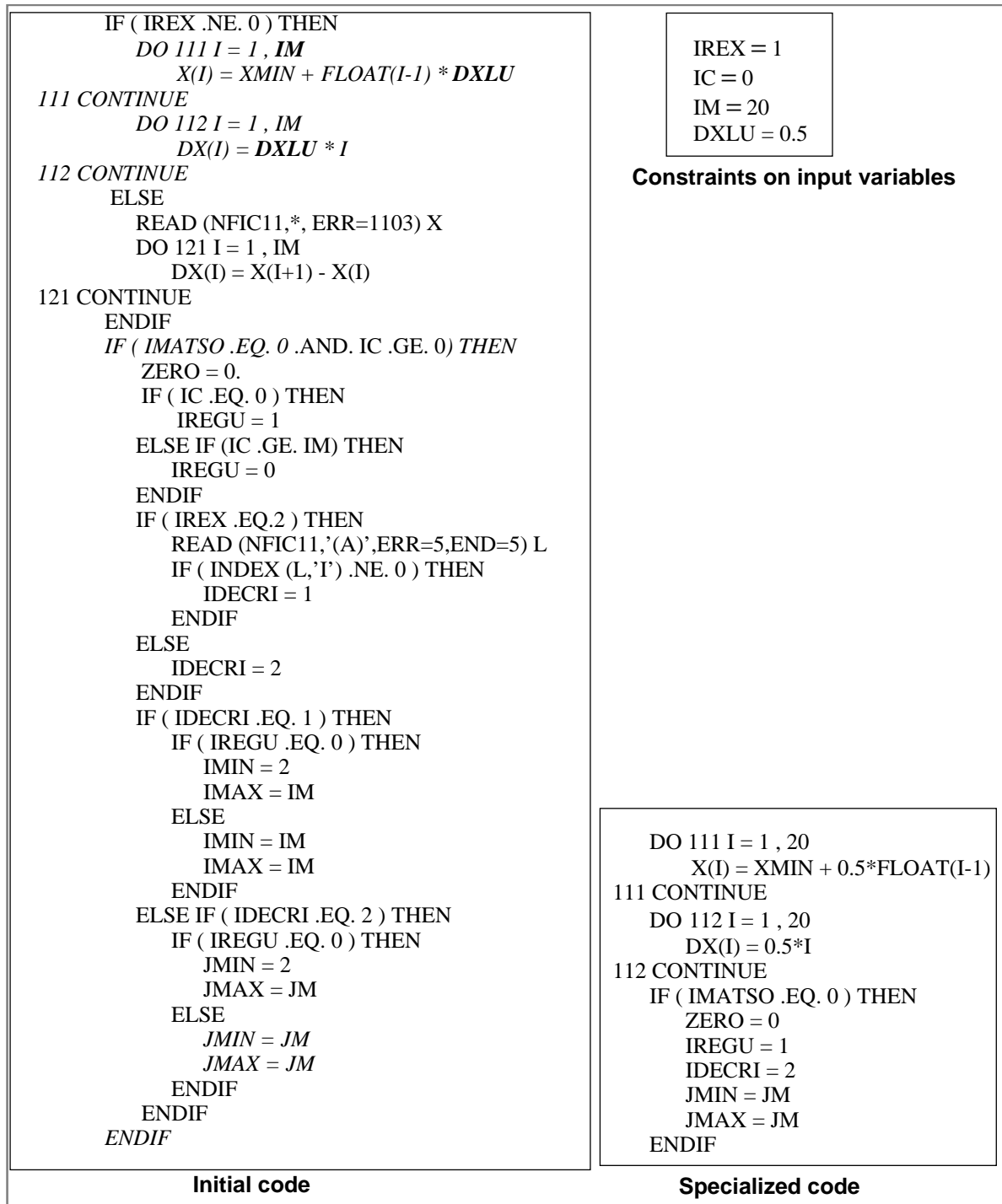
**Fig. 1. Some constraints on input data**

- the tool allows the user to formulate hypotheses about the code and investigate whether they hold or must be rejected. As detailed in [14] such a process is one of the major components of dynamic code cognition behaviors. The tool helps to find parts of lost code semantics. A bug is mentioned by a team maintaining a specific application program. For instance, it maintains only the application program applied to the geometry detailed in Fig.1. The tool aims at specializing the application program according to specific values of such variables. Another example is the specialization of a 3D-application program into a 2D-one by fixing the value of a co-ordinate.

- the tool does not change the original structure of the application program as explained in [3]. The tool is based on partial evaluation but we have adapted partial evaluation for program understanding. In traditional specialization, call statements are unfolded "on the fly": during specialization the call is replaced by a copy of the statements of the called subroutine, where every argument expression is substituted for the corresponding formal parameter [9]. This strategy aims at improving efficiency of programs. As our goal is to facilitate the comprehension of programs, we do not change their structure (as explained in [3]). We do not unfold statements. With such a strategy, the size of the code does not increase. Thus, we are neither faced with the problem of infinite unfolding and termination of the specialization process nor with the problem of duplication of code (recursion does not exist in Fortran 77).

We have presented in previous papers ([3]-[5]) the development and experiments of a first version of our tool. We give in (see next page) an example of the program specialization performed by this version. In that first version, no interprocedural analysis was really performed: at each procedure call, the most pessimistic hypothesis about possible changes of variables values was applied and the user had to run the tool on each procedure. As most programs we analyze are large-scale Fortran programs, made of many procedures with complex interactions, that limitation was really too severe. Thus we decided to extend the tool by a very precise interprocedural analysis.

Our software maintenance tool must introduce absolutely no unforeseen changes in programs. Therefore, we have first specified the specializer, then we have proven the correctness of that specification with respect to the standard semantics. [5] details this development process in a general framework. This paper describes how we have specified, implemented, and used interprocedural analysis to improve our tool for a better program understanding. Section 2 explains our interprocedural specialization strategy for Fortran programs. Section 3 gives some definitions and shows which data are needed for the specialization of procedures. Section 4 details the interprocedural specialization process. Section 5 is devoted to the implementation of that interprocedural analysis and section 6 offers conclusions and future work.



**Fig. 2. An example of code specialization (without interprocedural analysis)**

## 2 An interprocedural specialization strategy

Fortran 77 [6] characteristics for interprocedural specialization mainly concern static side-effects. Fortran procedures may be subroutines or functions and parameters are passed by reference. In Fortran, variables are usually local entities. However, variables may be grouped in common blocks (a common block is a contiguous area of memory) and thus shared in procedures. Common blocks may also be inherited in a procedure. They have a scope in that procedure but they have not been declared in it.

Local variables in a procedure do not necessarily retain their values between invocations of that procedure. At any instant in the execution of a program, if a common block is neither declared in the currently executing procedure nor in any of the procedures in the chain of callers, all of the variables in that common block also become undefined. The only exceptions are variables that have been defined in a DATA statement (this statement allows to initialize variables) and never changed. Variables may be made remanent by a SAVE statement. It specifies that certain variables and common blocks retain their values between invocations. Constants may also be defined by a PARAMETER statement (for example, PARAMETER pi=3.1416). Once defined, a constant can not be redefined in another statement).

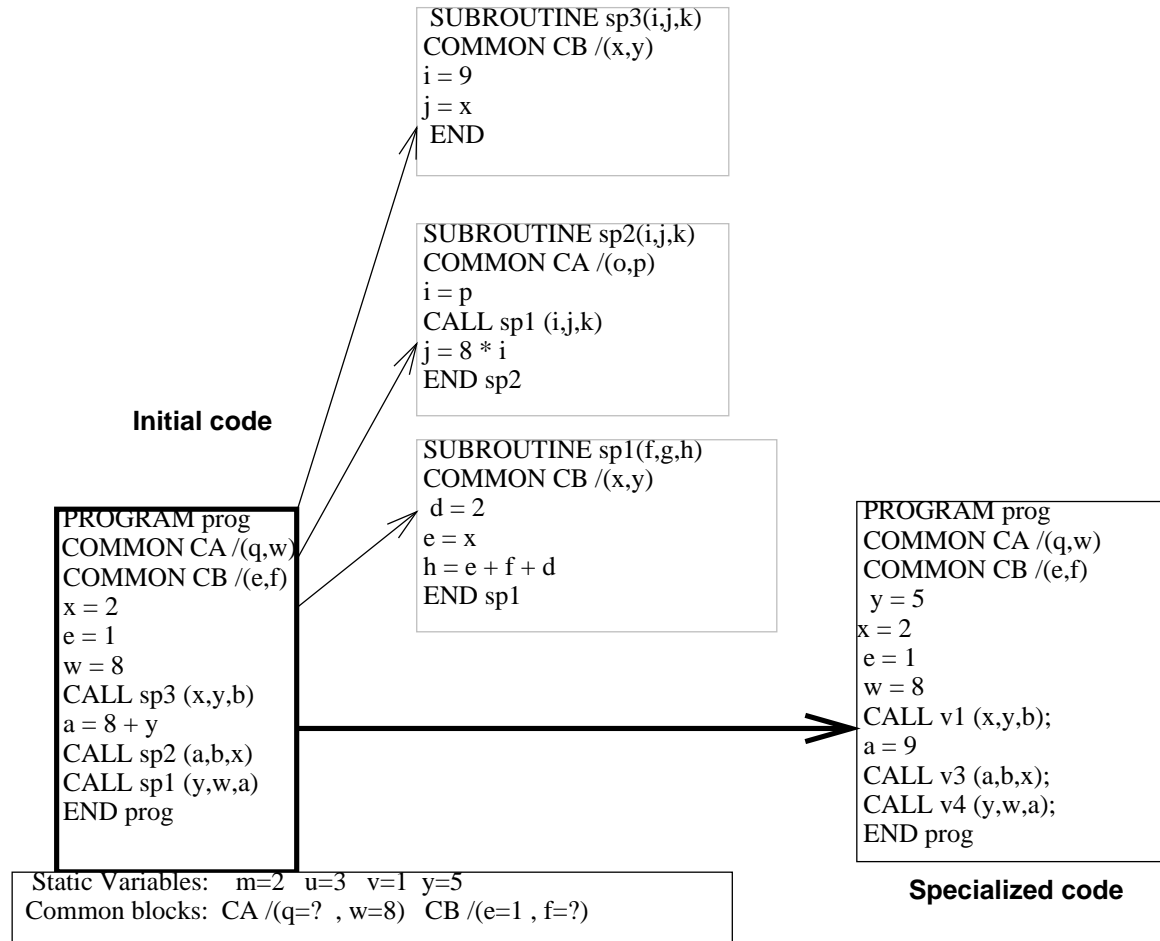
Program specialization processes are based on propagation of static data. As far as we are concerned, these are variables, parameters or common blocks. Static data may be remanent data. Procedure specialization aims at specializing a procedure with respect to static data: static variables (as in specialization of other statements) and also static parameters and static common blocks. The specialization must proceed depth-first to preserve the order of side-effects [2]. This means that a procedure must be specialized before the statements following its call.

To improve the specialization, specialized procedures and their initial and final static data are kept and reused if necessary. Thus, in a program, when several calls to a same procedure are encountered, in the current call if the static data is:

- the *same* as static data of a previous call, then the corresponding version is directly reused,
- *strictly included* in static data of a previous call, then the corresponding version is specialized and added to the list of specialized versions. If several versions match, the most specialized version is selected. It is the most restrictive (default strategy): its number of static data is the biggest. If again several versions match, then the shortest version is selected.

The number of versions of a procedure may theoretically grow exponentially, but our experiments showed that this seldom happens. However, as the number of specialized versions is finite (an option of the specializer allows to change it), if a version must be removed (from the list of versions), either the most restrictive or the most general one is removed. With a general strategy, specialized procedures are more often reused than in the general strategy, but more statements should also be specialized. In a general framework and without any further analysis on the call graph, both strategies are worthwhile, depending on the application to specialize. Thus, an option of the specializer allows to change this strategy and to keep preferably the most general procedures.

A version is characterized by its name, its statements and its initial and final static data. A version name is generated each time a new version is created. That name is added in the caller as a comment of the call and in the declaration of the specialized procedure. Fig. 3 (see next page) shows an example of interprocedural specialization. In this figure, ? stands for unknown values of (dynamic) variables.



#### Constraints on input variables

	Initial static data	Final static data	Version
v1 (sp3)	i=2 j=5 x=1 COMMON CA/ (?,8) COMMON CB/ (1, ?)	i=9 j=1 x=1 COMMON CA/ (?,8) COMMON CB/ (1, ?)	SUBROUTINE v1 (i,j,k) COMMON CB /(x,y) i = 9 j = <b>1</b> END v1
v2 (sp1)	f=8 h=9 x=1 COMMON CA/ (?,8) COMMON CB/ (1, ?)	d=2 e=1 f=8 h=11 x=1 COMMON CA/ (?,8) COMMON CB/ (1, ?)	SUBROUTINE v2 (f,g,h) COMMON CB /(x,y) d = 2 e = <b>1</b> h = <b>11</b> END v2
v3 (sp2)	i=9 k=9 p=8 COMMON CA/ (?,8) COMMON CB/ (1, ?)	i=8 j=64 k=11 p=8 COMMON CA/ (?,8) COMMON CB/ (1, ?)	SUBROUTINE v3(i,j,k) COMMON CA /(o,p) i = 8 CALL v2 (i,j,k) j = <b>64</b> END v3
v4 (sp1)	f=1 g=8 h=8 x=1 COMMON CA/ (?,8) COMMON CB/ (1, ?)	d=2 e=1 f=1 g=8 h=4 x=1 COMMON CA/ (?,8) COMMON CB/ (1, ?)	SUBROUTINE v4 (f,g,h) COMMON CB /(x,y) d = 2 e = <b>1</b> h = <b>4</b> END v4

**Fig. 3. An example of interprocedural specialization**

### 3 Notations for specifying interprocedural specialization

#### 3.1 Definitions

An expression is static if its subexpressions (expressions, variables, function calls, etc.) are all static. These expressions can be represented by a so-called environment, namely a function associating values to variables. For our interprocedural analysis, we need more information than such an environment to take into account side-effects due to parameters and common blocks.

We define in this section some useful notations and especially set operators to specify information that are useful for interprocedural specialization. In these specifications we use maps associating values to identifiers. A map is a finite function. It is represented by a set of pairs of the form  $x \rightarrow y$ , where no two pairs have the same first elements. The set of all other possible values is noted **Values**. **Ident** denotes the set of all identifiers. The **Eval** function either yields the value of an expression (if it is static) or gives a residual expression (if it is dynamic).

We introduce a data type constructor named composite type (also called record) and useful set operators, similar to those defined in the formal specification languages B [1] and VDM [8]: domain, range,  $\cup$ , override, various forms of restriction, composition, and finally direct product. These operators are written in bold in this paper.

- To create values of a composite type, a "make" function is used, called **mk- $T$**  ( $x_1, x_2, \dots$ ), where the  $x_i$  are the appropriate values for the fields  $T_i$  and the result is a value of type  $T$ .
- The domain (**dom**) (resp. range (**ran**)) operator applies to a map. It yields the set of the first (resp. second) elements of the pairs in the map.
- The union operator  $\cup$  is defined only on two maps whose domains are disjoint. Thus it yields a map which contains all pairs of the maps.
- The map override operator  $\dagger$  whose operands are two maps, yields a map which contains all of the pairs from the second map and those pairs of the first map whose first elements are not in the domain of the second map.
- The map restriction operator  $\triangleleft$  (resp.  $\triangleright$ ) is defined with a first operand which is a set (resp. a map) and a second operand which is a map (resp. a set); the result is all of those pairs in the map whose first (resp. second) elements are in the set.
- When applied to a set and a map, the map deletion operator  $\triangleleft$  (resp.  $\triangleright$ ) yields those pairs in the map whose first (resp. second) elements are not in the set.
- The forward composition  $r;p$  of two maps  $r$  and  $p$  the map made of pairs  $x \rightarrow z$  where there exists some  $y$  such that  $x \rightarrow y \in r$  and  $y \rightarrow z \in p$ .
- The direct product  $\otimes$  of two maps  $r$  and  $p$  is the map made of the pairs  $x \rightarrow (y \rightarrow z)$  where  $x \rightarrow y \in r$  and  $y \rightarrow z \in p$ .
- Given two maps  $m, n$  and a set of pairs of maps  $s$  we define **Corres** ( $m, n$ ) and **GalCorres** ( $s$ ) such that: **Corres** ( $m, n$ ) = **ran** ( $m \otimes n$ ) and **GalCorres** ( $s$ ) =  $\cup \{ \text{Corres} (m, n) \mid m \rightarrow n \in s \}$ . **Corres** and **GalCorres** are relations (not necessary maps) but in this paper we use them only in contexts where they are maps. **GalCorres** ( $s$ ) is only applied to maps **Corres** ( $m, n$ ) with pairwise disjoint domains.



The two following examples show how both relations are used in the framework of an interprocedural analysis.

**Ex1.** Let  $Formal = \{1 \rightarrow a, 2 \rightarrow b\}$  and  $LParam = \{1 \rightarrow x+y, 2 \rightarrow 27\}$ .

Then,  $\mathbf{Corres}(Formal, LParam) = \mathbf{ran}(\{1 \rightarrow (a \rightarrow x+y), 2 \rightarrow (b \rightarrow 27)\}) = \{a \rightarrow x+y, b \rightarrow 27\}$ .  $\square$

**Ex2.** Let  $ComDecl = \{A \rightarrow \{1 \rightarrow e, 2 \rightarrow f\}, D \rightarrow \{1 \rightarrow l, 2 \rightarrow m\}\}$  and

$ComVal = \{A \rightarrow \{1 \rightarrow 2, 2 \rightarrow 4\}, B \rightarrow \{1 \rightarrow 8, 2 \rightarrow 1\}, D \rightarrow \{1 \rightarrow 5, 2 \rightarrow 7\}\}$ .

Then,  $\mathbf{ran}(ComDecl \otimes ComVal) =$

$$\mathbf{ran}(\{A \rightarrow (\{1 \rightarrow e, 2 \rightarrow f\} \rightarrow \{1 \rightarrow 2, 2 \rightarrow 4\}), D \rightarrow (\{1 \rightarrow l, 2 \rightarrow m\} \rightarrow \{1 \rightarrow 5, 2 \rightarrow 7\})\}) = \\ \{ \{1 \rightarrow e, 2 \rightarrow f\} \rightarrow \{1 \rightarrow 2, 2 \rightarrow 4\}, \{1 \rightarrow l, 2 \rightarrow m\} \rightarrow \{1 \rightarrow 5, 2 \rightarrow 7\} \}$$

and  $\mathbf{GalCorres}(\mathbf{ran}(ComDecl \otimes ComVal)) =$

$$\mathbf{Corres}(\{1 \rightarrow e, 2 \rightarrow f\}, \{1 \rightarrow 2, 2 \rightarrow 4\}) \cup \mathbf{Corres}(\{1 \rightarrow l, 2 \rightarrow m\}, \{1 \rightarrow 5, 2 \rightarrow 7\}) \\ = \{e \rightarrow 2, f \rightarrow 4, l \rightarrow 5, m \rightarrow 7\}. \quad \square$$

### 3.2 Propagated data

During interprocedural specialization, data are propagated through statements in order to simplify them. They mainly store definitions of Fortran objects (formal parameters, common blocks, etc.) and relations between variables and values. The values are related to a program point. First, this section details these data. Then, it specifies how they are modified during the specialization of procedures.

Information associated to the current program point consist of:

- an environment ( $Env$ ) providing information that do not change in the program. These are:
  - formal parameters ( $Formal$ ). It maps integers (the positions in the list of formal parameters) to the names of the corresponding formal parameters. For instance, the map corresponding to the declaration `SUBROUTINE SP(a,b,c)` is  $\{1 \rightarrow a, 2 \rightarrow b, 3 \rightarrow c\}$ .
  - declared common blocks ( $ComDecl$ ). They are similarly represented by a mapping from common block names to the maps of their variable names. For instance, the map corresponding to the declarations `COMMON A/e,f` and `COMMON D/l,m` is the following map:  $\{A \rightarrow \{1 \rightarrow e, 2 \rightarrow f\}, D \rightarrow \{1 \rightarrow l, 2 \rightarrow m\}\}$ . The order of variable names associated to common blocks must be kept in the map because of the correspondence between the variables of a common block: the variable names of a same common block may vary from a procedure to another, and their values are passed solely thanks to the position of the variable in the declaration of the common block.
  - saved data ( $SavData$ ).  $SavData$  is the set of variables and common block names that have become remanent after a `SAVE` statement. For instance, the set corresponding to both statements `SAVE COMMON A` and `SAVE X,Y` is  $\{A,X,Y\}$ .
  - initialized data ( $InitData$ ). Variables defined in a `DATA` statement and constants defined in a `PARAMETER` statement are initialized data.  $InitData$  maps their names to their initialized values.
  - statements of the program ( $Stmts$ ).
- a state ( $State$ ) representing relations between variables and values. The type of  $State$  is the composite type  $TState$  which fields  $SV$  and  $ComVal$  are:

- the mapping (*SV*) from Static variables to their current Values. If interprocedural analysis would not have been performed, only this map would have been used to specialize programs, as it was done in [4].
- the mapping (*ComVal*) between common block names and the values of their static variables. For instance, in the map  $ComVal = \{ A \rightarrow \{ 3 \rightarrow 2 \} \}$  the common named *A* is such that its third variable evaluates to 2 and its other variables are dynamic.
- the mapping (*Called*) between names of called procedures and pairs. Such a pair consists of:
  - the environment (*EnvCalled*) of the called procedure,
  - the specialized versions (*Versions*) of the called procedure. This is a set made of quadruples (*Name*, *Input*, *Output*, *V*), where the data type of *Input* and *Output* is *TState*, *V* denotes the whole specialized procedure and *Name* denotes the name of the procedure *V*. The **add** primitive adds a quadruple to a set of versions.
- the inherited common blocks of the current procedure *P* (*ComInh*). The common block names belonging to this set are declared in one of the procedures of the chain of callers, but not in *P*.

## 4 Interprocedural specialization

Our specializer performs two main tasks: data propagation through the code and simplification of statements. Both tasks are detailed in [3]. In this section, we specify the propagation through a call-statement and the simplification of a call-statement.

### 4.1 The propagation process

While encountering a call-statement, the propagation process propagates first the current state of the caller through the called procedure. Then, a most specialized version is selected, yielding an updated state. Last, the code generation process is returned to the calling procedure and the state is propagated through the caller, because of side-effects.

In the sequel of this paper, *EnvSP* denotes the environment of the current called procedure, that is  $EnvSP \triangleq Called(SP).EnvCalled$ . During the propagation through the called procedure formal parameters, local variables and common blocks of the called procedure *SP* modify the current state:

- If a local variable *V* is initialized in *SP* by a value, this value becomes the new value of *V* whether *V* had a value in the static variables *State.SV* or not. Thus, *State.SV* becomes  $State.SV \dagger EnvSP.InitData$ .
- Due to correspondences between actual and formal parameters and also between variables of same common blocks, formal parameters and variables of declared common blocks may become static. In this case, they are added in the current state. Thus, the forward propagation updates the current state in the following way. *State.SV* becomes *Input*, with:

$$Input \triangleq (State.SV \dagger EnvSP.InitData) \cup (StaticFormal \dagger StaticCom)$$

The definitions of *StaticFormal* and *StaticCom* are explained below. As formal (resp. actual) parameters are specified by a map named *Formal* (resp. *LParam*) from integers (the ranks of parameters in the list) to the names of parameters, the link between these formal and actual parameters is specified by the map **Corres** ( $EnvSP.Formal, LParam$ ) (see Ex.1 for an example of such a map). Furthermore, only static actual parameters give values to their corresponding static formal parameters. Thus, these static formal parameters are:

$StaticFormal \triangle \text{Corres} (EnvSP.Formal, LParam) ; \text{eval} (State.SV) \triangleright \text{Values}$ ,

where  $;\text{eval} (State.SV)$  evaluates actual parameters that are expressions, and  $\triangleright \text{Values}$  restricts this result to static formal parameters.

Static common blocks of the caller are either inherited in the called procedure or declared in the caller. Thus, the set of all common block names is  $\text{dom} (Env.ComDecl) \cup ComInh$ . The common blocks that are inherited by the called procedure are the whole common blocks except those that are re-declared in it, that is  $\text{dom} (Env.ComDecl) \cup ComInh - \text{dom} (EnvSP.ComDecl)$ .

Given a common block  $C$  that is declared or inherited in the caller, if  $V$  is the  $n$ 'th variable of  $C$ , then its corresponding variable  $V'$  in a called procedure  $SP$  is the  $n$ 'th variable of  $C$ . If  $C$  is declared between the caller and  $SP$  (in the chain of callers), the names of  $V$  and  $V'$  may differ, but these variables share common values. For instance, at the program point  $\text{call } SP(LParam)$ , the value of  $V$  is the initial value of  $V'$ . Thus, if  $V$  is static, then  $V'$  is initially static (with the same value of  $V$ ). This transmission of values from common blocks of the caller to corresponding common blocks of the called procedure is specified by the map  $\text{GalCorres} [\text{ran} (EnvSP.ComDecl \otimes State.ComVal)] \triangleright \text{Values}$ .

$StaticCom1 \triangle \text{GalCorres} [\text{ran} (EnvSP.ComDecl \otimes State.ComVal)]$

**Ex.3.** If the called procedure  $SP$  is such as  $State.SV = \{i \rightarrow 5, j \rightarrow 3, a \rightarrow 1\}$  with the following declarations (without initialized data)  $\text{COMMON } A/e, f, g$  and  $\text{COMMON } D/l, m$ , then:

$EnvSP.ComDecl = \{A \rightarrow \{1 \rightarrow e, 2 \rightarrow f\}, D \rightarrow \{1 \rightarrow l, 2 \rightarrow m\}\}$ .

If for instance  $ComVal = \{A \rightarrow \{1 \rightarrow 2, 2 \rightarrow 4\}, B \rightarrow \{2 \rightarrow 1\}, D \rightarrow \{1 \rightarrow 5\}\}$ , then (from Ex.2):

$\text{GalCorres} [\text{ran} (EnvSP.ComDecl \otimes ComVal)] \triangleright \text{Values} = \{e \rightarrow 2, f \rightarrow 4, l \rightarrow 5\}$ .

Thus,  $State.SV$  becomes  $\{e \rightarrow 2, f \rightarrow 4, l \rightarrow 5, i \rightarrow 5, j \rightarrow 3, a \rightarrow 1, b \rightarrow 3\}$ . End of Ex.3  $\square$

Last, common blocks that have a scope in the caller are either declared or inherited in the caller. These are  $\text{dom} (ComDecl) \cup ComInh$ . They are inherited by the called procedure  $SP$  except if they are re-declared in this procedure. Thus, these common blocks are:

$ComInh' \triangle \text{dom} (Env.ComDecl) \cup ComInh - \text{dom} (EnvSP.ComDecl)$ .

The fields of the state ( $State1$ ) resulting from the propagation through the called procedure are  $Input$  and  $StaticCom1$ , that is  $State1 \triangle \text{mk-TState} (Input, StaticCom1)$ . After this first propagation,  $State1$  and the environment of the called procedure are propagated through the statements of the called procedure, yielding a state  $State2$  (propagation rule). Then, the propagation through the caller is performed.

As in the propagation through the called procedure, actual parameters, local variables and common blocks of the caller may become static and modify the current state  $State2$ . In  $State2$ , the new values of the actual parameters (resp. common blocks) become  $StaticActual$  (resp.  $StaticCom2$ ) whether they had a value in the state or not. Thus,  $State2.SV$  becomes  $State2.SV \dagger StaticActual \dagger StaticCom$ . This map is restricted to remanent variables: data saved in the called procedure are removed from the current state. Thus, the final state is:

$SV' \triangle EnvSP.SavData \triangleleft (State2.SV \dagger StaticActual \dagger StaticCom2)$ .

The definitions of  $StaticActual$  and  $StaticCom2$  are given below. In the called procedure, if a formal parameter is:

- dynamic, then in the state its corresponding actual parameter is suppressed from the static data,
- static, then its value becomes the new value of the corresponding actual parameter, whatever its previous value was.

**Corres** ( $LParam, Formal$ ); **eval** ( $State2.SV$ )  $\triangleright$  **Values** maps actual parameters to their corresponding static formal parameters, as in the definition of *StaticFormal*. As expressions are not handled in static variables maps even if they are static, this map is restricted to identified actual parameters (information such as  $x+y$  evaluates to 3 are lost). Thus, the static actual parameters are:

$$StaticActual \triangleq \text{ident} \triangleleft (SV \uparrow (\text{Corres } (LParam, Formal) ; \text{eval } (State2.SV) \triangleright \text{Values})).$$

In the caller, the values of some static variables of common blocks are updated in a similar way. These are variables whose value is given by the map *State2.Common*. Thus, in the caller the static variables of common blocks are:

$$StaticCom2 \triangleq \text{GalCorres}[\text{ran } (Env.ComDecl \otimes State2.ComVal)].$$

Last, in the called procedure, remanent common blocks (*RemCom*) have become remanent by a SAVE statement of the called procedure (they belong to *EnvSP.SavData*), or they exist in the called procedure (either they have been declared in it or they have been inherited from the caller). Thus:

$$RemCom \triangleq \text{dom } (EnvSP.ComDecl) \cup ComInh' \cup EnvSP.SavData.$$

*State2.ComVal* maps static variables of common blocks to their corresponding values. These are common blocks of the caller if remanent common blocks of the called procedure have been removed from the map. Thus, *Env.ComVal* becomes *ComVal'* with:

$$ComVal' \triangleq RemCom \triangleleft State2.ComVal.$$

The fields of the final state *State'* are *SV'* and *ComVal'*, that is *State'*  $\triangleq \text{mk-TState } (SV', ComVal')$ .

Fig. 4. recalls whole definitions and the corresponding propagation rule explained in this section. While implementing such rules, variables should be replaced in the rules by their definition.

### Definitions

$EnvSP \triangleq Called(SP).EnvCalled$

#### Caller $\rightarrow$ called propagation

$StaticFormal \triangleq \mathbf{Corres} (EnvSP.Formal, LParam) ; \mathbf{eval} (State.SV) \triangleright \mathbf{Values}$

$StaticCom1 \triangleq \mathbf{GalCorres}[\mathbf{ran} (EnvSP.ComDecl \otimes State.ComVal)]$

$Input \triangleq (State.SV \dagger EnvSP.InitData) \cup (StaticFormal \dagger StaticCom1)$

$ComInh' \triangleq \mathbf{dom} (Env.ComDecl) \cup ComInh - \mathbf{dom} (EnvSP.ComDecl)$

$State1 \triangleq \mathbf{mk-TState} (Input, StaticCom1)$

#### Called $\rightarrow$ caller propagation

$StaticActual \triangleq \mathbf{ident} \triangleleft [\mathbf{Corres} (LParam, EnvSP.Formal) ; \mathbf{eval} (State2.SV)] \triangleright \mathbf{Values}$

$StaticCom2 \triangleq \mathbf{GalCorres} [\mathbf{ran} (Env.ComDecl \otimes State2.ComVal)]$

$SV' \triangleq EnvSP.SavData \triangleleft (State2.SV \dagger StaticActual \dagger StaticCom2)$

$RemCom \triangleq \mathbf{dom} (EnvSP.ComDecl) \cup ComInh' \cup EnvSP.SavData$

$ComVal' \triangleq RemCom \triangleleft State2.ComVal$

$State' \triangleq \mathbf{mk-TState} (SV', ComVal')$

#### Propagation rule

$Called(SP).Env, State1, ComInh', Called \vdash EnvSP.Stmts : State2$

---

$Env, State, ComInh, Called \vdash \mathbf{call} SP (LParam) : State'$

**Fig. 4. Propagation of call-statements**

## 4.2 Simplification

While simplifying a call-statement, the specializer checks first whether the called procedure has been specialized in a similar context (that is with the same or less restrictive static data) before. Three situations may happen. They correspond to the three rules of Fig. 5. and are:

- the called procedure  $SP$  has already been specialized into  $V$  with the same static data ( $Input$ ). Thus,  $V$  becomes the specialized procedure of the subject procedure  $SP$  (first rule).

- the procedure is not as specialized as wanted (second rule). For instance the last parameter of the procedure to specialize is static, but the last parameter of the most specialized version is dynamic. Then, one of the most specialized versions (*Version*) and its output static data (*Output*) are selected among the versions such that the cardinal of their input static data is the biggest. Note that its static variables and parameters are strictly included in those of the subject procedure, and its common blocks, that have also a scope in the subject procedure, are such that each of their static variables has the same value in both common blocks. Thus, *Version* and *Output* are:

$$Version, Output \triangleq \text{any } V, O \text{ such that } (N, In, O, V) \in Called(SP).Versions \wedge Input \subset In \wedge \\ (\nexists (N', J, O, V') \in Called(SP).Versions \text{ such that } Input \subset J \subsetneq In)$$

The selected procedure is then specialized (as in the following situation) and the name of the specialized procedure (*NewName*) is selected among the set **NAME** of possible names, that have not been already selected as procedure names.

- the called procedure has not been specialized. A residual procedure is specialized from it, a new name is computed and the current state is modified by the results of the specialization (third rule).

### Definitions

*Version, Output*  $\triangleq$  any  $V, O$  such that  $(In, O, V) \in Called(SP).Versions \wedge Input \subset In \wedge$   
 $(\exists (J, O, V') \in Called(SP).Versions \text{ such that } Input \subset J \subset In)$

*SelectedNames*  $\triangleq \{N \mid (N, I, O, V) \in \mathbf{ran} (Called).Versions\}$

### Simplification rules

**Rule 1: the called pocedure has already been specialized with the same static data**

$(Name, State1.SV, Out, V) \in Called(SP).Versions$

*Propagation*

$EnvSP, Output, ComInh', Called \vdash V : State2$

(1)

---

$Env, State, ComInh, Called \vdash \mathbf{call} SP (LParam) \rightarrow \mathbf{call} NewName (LParam)$

**Rule 2: the called procedure is not as specialized as wanted**

$\{(Name, In, Out, V) \in Called(SP).Versions \mid State1.SV \subsetneq In\} \neq \emptyset$

$EnvSP, Output, ComInh', Called \vdash Version \rightarrow SP'$

*Propagation*

$EnvSP, Output, ComInh', Called \vdash SP' : State2$

**add**  $((NewName, State.Variables, State2.Variables, SP'), Called(SP).Versions)$

$NewName \in \mathbf{NAME} - SelectedNames$

(2)

---

$Env, State, ComInh, Called \vdash \mathbf{call} SP (LParam) \rightarrow \mathbf{call} NewName (LParam)$

**Rule 3: the called procedure has not been specialized**

$\{(Name, In, Out, V) \in Called(SP).Versions \mid State1.SV \subsetneq In\} = \emptyset$

$EnvSP, State1, ComInh', Called \vdash EnvSP.Stmts \rightarrow SP'$

*Propagation*

$EnvSP, State1, ComInh', Called \vdash SP' : State2$

**add**  $((NewName, State.Variables, State2.Variables, SP'), Called(SP).Versions)$

$NewName \in \mathbf{NAME} - SelectedNames$

(3)

---

$Env, State, ComInh, Called \vdash \mathbf{call} SP (LParam) \rightarrow \mathbf{call} NewName (LParam)$

**Fig. 5. Simplification of call-statements**

## 5 Implementation

We have implemented our specification rules as such in our tool where B and VDM operators have been translated into Prolog. This process is the same as those followed in [4] and [11]. The tool is fully automated. A debugger allows to apply the rules step by step. This is useful while trying to understand the behavior of a residual program. For instance, with such a debugger, the user may know at any program point the static values and then understand either why a then-branch of an alternative has been removed and not the else-branch, as he would have thought, or why a function does not yields the expected result.

We have used natural semantics to write our specification rules. Natural semantics gives a formalism to write inference rules, but it does not provide any formalism to describe (and decompose) the environments appearing in the rules. Without interprocedural analysis, such an environment was a single SV-like map. This map was thus a variable in the inference rules. But with an interprocedural analysis, given the environments we propagate, we can not afford to show to the user all the environment variables appearing in the rules. Thus, the environments are pretty-printed in a user-friendly style (which is close to Fortran). Instead of showing directly the mathematical variables that are used in environments, only information that are relevant for the user (for instance information related to common blocks) are visualized. For instance  $\text{COMMON } A / e = 2, f = u$  is pretty-printed instead of  $\text{Env.ComDecl} = \{A \rightarrow \{1 \rightarrow e, 2 \rightarrow f\}\}$ ,  $\text{State.ComVal} = \{A \rightarrow \{1 \rightarrow 2, 2 \rightarrow u\}\}$ .

## 6 Conclusion

We have explained how to extend by interprocedural analysis our program specialization technique for program understanding. That analysis is especially difficult in Fortran, due to the lack of well defined interprocedural mechanisms and the complexity of visibility rules. Therefore we have designed these extensions very carefully, starting with a formal specification of the information to be computed. These extensions are now integrated in our tool and they allow us to specialize complex programs with much greater precision than previously. Information is propagated along procedure calls, and specialized versions of the called procedures are proposed to the maintainer.

The first experiments with these extensions have given very satisfactory results. Some improvements are now under consideration. For instance a good strategy for reuse of procedure specializations must be developed. Furthermore the information we compute for interprocedural specialization are of great interest by themselves, in the program comprehension process, independently of its particular use in specialization. Therefore we develop ways to show it in a user-friendly shape.

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