Investigating the Integration of two Formal Methods

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Abstract. VDM and B are two mature formal methods currently in use by industry and supported by commercial tools. Though the methods are foundationally similar, the coverage of their supporting tools differ significantly. The SPECTRUM project has investigated the feasibility of integrating support for the two methodologies. In this paper, we describe the project and report on some technical results.

1. Background

VDM [Jon90] and B [Abr96] are two formal methods currently in use by industry and supported by mature commercial tools. The methods are essentially similar. Both are model-oriented methods for the development of sequential systems based on first order predicate calculus and set theory. Both have a set of proof rules defined for formal verification and validation. Both have a formal semantics: for B this is defined in terms of weakest preconditions, for VDM it is denotational.

However, the coverage of the supporting tools for VDM [ELL94] and B [BCORE] differ significantly in their capabilities for static analysis, proof, animation and code generation. This complementary functionality could benefit users from both communities, but because of the differences between the methods such cooperation is not currently possible. This paper reports progress towards the integration of these methods and tools within the EC project SPECTRUM¹.

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1.1. VDM

VDM's origins lie in the definition of programming language semantics in the 1970s, but for many years it has been used in systems specification and development generally, and there is now an ISO standard [ISO96] of the specification language VDM-SL. It has a rich set of data type constructors, augmented by invariant predicates. Functions and state-transforming operations can be defined explicitly using a large expression and statement language or implicitly in terms of precondition and postcondition predicates.

The VDM-SL standard includes a denotational semantics [LaP95]. In particular, the strong type system supports static detection of many well-formedness errors. A published proof theory, described in [Jon90] and in greater detail in [BFL94], supports the validation of VDM-SL specifications through the discharge of proof obligations. The semantics is based on the three-valued Logic of Partial Functions (LPF [JoM94]) which explicitly deals with definedness of expressions and requires the demonstration of well-typing for the substitution of equals.

One area of weakness in VDM relative to B is its lack of generally agreed large-scale structuring. The standard contains a “informative annex” describing several alternative approaches to modules, including one implemented within the IFAD Toolbox and other structuring proposals exist [Fit91].

The IFAD VDM-SL Toolbox [ELL94] is an industrial strength commercially available tool which supports the ISO VDM-SL notation. The Toolbox includes a syntax checker, static semantic checker, and a pretty printer generating LaTeX output. In addition, it contains a debugger, an interpreter, and a C++ code generator. It is also possible to perform test coverage analysis of specifications.

Other tools produced for VDM have included: Mural [JLL91] concentrating on proof obligation generation and discharge; SpecBox [SPEC] providing a parser, typechecker, semantic analyser and pretty-printer; the VDM Analysis Tool [DiF93] which provides test case generation; and VDM Through Pictures [DiL91] supporting the generation of VDM “skeletons” from Entity-Relationship style diagrams.

1.2. B

The B-Method [Abr96] represents one of the most comprehensive formal methods currently being promoted as appropriate for commercial use. A development of VDM and Z, Jean-Raymond Abrial originated **B** whilst at the Programming Research Group at Oxford University in the early 1980s, and subsequently at British Petroleum Research (BP) and DIGILOG.

The method uses Abstract Machine Notation (AMN) which uses a notion of *generalised substitution* to represent state transformations, a style of specifying operations which is more “natural” to the programmer. The B-method also has powerful structuring mechanisms based on a notion of *Abstract Machine* which offers data encapsulation allowing modular design and development of systems.

B's underlying semantics is grounded in weakest preconditions over untyped set theory and classical logic; the type system is correspondingly weak, and the distinction between type-checking and proof is blurred.

The B-Toolkit [BCORE], developed by BP and subsequently by B-Core UK Ltd is an industrial strength commercially available tool to support formal de-

velopment in B. It focuses on rigorous/formal design by supporting refinement from abstract specification through to imperative code. Tools exist for supporting static analysis (type-checking), dynamic analysis (animation), design documentation, proof of refinement and code generation. Another commercial support system is Atelier-B [Ate], provided by Steria Méditerranée which allows similar functionality to the B-Core Toolkit.

1.3. Combining the Two Methods

The combination of VDM and B was first explored in the MaFMeth Project [BDW96, BDM97]. This demonstrated that developing systems using a combination of B and VDM was both possible and useful. This project developed part of a transaction management system using VDM for the initial design and analysis and then translating into B for development and code generation. It was found that VDM encouraged a more abstract initial design, allowing clarity of expression, while B allowed more of a programming style suitable for the later stages of development. The formal notations allowed the use of many types of formal analysis, including syntactic and static analysis, test case generation, animation, formal proof, and code generation. Design features and errors were discovered at each analysis emphasising that the more analyses which can be brought to bear on a design the better.

The use of the combination of the two methods did however have problems. Errors were introduced in the translation between notations which was unsupported. Despite this, results of the study were favourable in terms of the total number of errors in the development, the early detection of errors and the overall effort expended.

Earlier work [BiR93], however, had shown that the languages are not trivially interchangeable. As well as the differences in structuring mechanisms, there are significant differences between the languages in their use of invariants, frames and postconditions. Furthermore there are significant differences between the languages in their underlying semantics and proof theories. B is based on classical logic whereas VDM uses the LPF which explicitly handles partial functions. This leads to a different treatment of termination and definedness.

Whilst we recognise that the two notations have some differences in interpretation, we believe that the semantics are sufficiently similar for interoperability to be meaningful and useful. In this paper, we discuss the feasibility of integrating the two languages.

2. The Spectrum Programme

The two methods are thus complementary in their styles: VDM is well-suited for requirements capture and high-level design, and B for subsequent development and code-generation. This is reflected by the functionality for various lifecycle tasks offered by the existing toolkits (see table 1). Support is best provided in those areas where each method is strong.

These observations have motivated the SPECTRUM programme which seeks to exploit this complementary nature by allowing the use of both languages within a single development process, including the integrated use of both toolkits. The first phase of this programme was the SPECTRUM project, a feasibility

Table 1. Table showing the complementary nature of the Toolkits.

Task	IFAD VDM-SL Toolbox	B-Toolkit
Requirements capture	×	×
Visualisation	×	×
Abstract Specification	✓	×
Type checking	✓	~
Prototype code generation	✓	~
Test coverage	✓	×
Animation/Execution	✓	✓
Modularity	~	✓
Refinement	×	✓
Proof	×	✓
Final Code generation	×	✓
Design documentation	×	✓
Version Control/Config Mgmt	×	~

✓ good support; ~ some support; × no support.

study which brought together four industrial users of formal methods in various safety-critical domains, the commercial suppliers of the VDM-SL Toolbox and the B-Toolkit, and a research laboratory with a mission of technology transfer. This feasibility study had three objectives:

- to assess the cost-effectiveness for the user partners, of a development process employing an integration of the VDM and B formal technologies,
- to determine the technical feasibility of this integration; and
- to investigate the commercial potential for the tool suppliers of the integration of supported forms of VDM and B.

The first objective was addressed through the development of user scenarios exploring the utility of the various functions available from the two toolkits and the advantages of employing them in terms of development cost and product quality. The scenarios were in the application domains of avionics systems and terrestrial transport embedded control. They were also reviewed from the perspectives of satellite communication control and nuclear power plant control. This work is reported elsewhere [Dra97, ALR98].

To address the third objective, the project assessed the commercial case for the provision of required functionality. It explored the overall cost-benefits of introducing the proposed method and the commercial viability of the proposed tool integration.

The remainder of this paper considers the second objective, the technical feasibility of the proposed integration. In this section, we describe the approach adopted based on translation between notations and in Sections 3 and 4, we describe the translations from B to VDM and from VDM to B respectively. The final section draws some conclusions.

2.1. The SPECTRUM Lifecycle

Figure 1 outlines the coverage of the VDM and B methods in terms of the classic V-lifecycle. VDM is seen as appropriate for high-level specification and analysis in the early stages of the development; B is more appropriate for low-level design and implementation. This approach must be supported by a facility

Fig. 1. The Lifecycle identified in the SPECTRUM project.

for moving from a VDM-SL model to a B model, which can be used as a starting point for refinement towards a B implementation machine from which code can be generated. At each stage of the development, verification with respect to the previous level is performed, and during implementation phases, testing is performed with respect to the appropriate level of the formal design.

As a consequence, in this lifecycle, the integration of VDM and B is required in two circumstances: translation from VDM-SL to B within the design process, and translations from B to VDM-SL within the testing phase.

2.2. Integration through Translation

We have seen that while the VDM-SL and B-AMN notations have broadly similar constructs and address similar problem areas, the two notations place different emphases on state structure, and on type and value expressivity. VDM provides a rich type definition language, and a similarly rich language of expressions and functions, but (relative to AMN) its state model is monolithic: in effect, the state model of a VDM-SL specification is a single variable of a complex type, and operations act on the state as a whole. On the other hand, whilst AMN provides a rich language for state modularisation, its type and expression notations are impoverished relative to VDM-SL. The state of a B specification consists of a relatively large number of state variables, usually of simple types, spread across a number of machines, each of which has operations acting primarily on the local state.

Thus, in translating between VDM-SL and AMN, two problems must be addressed: firstly how to represent the types and expressions of each language in the other, and secondly, how to relate the different complexities of structuring of the two languages. We first consider the translation of B-AMN to VDM-SL, and then VDM-SL to B-AMN.

3. Translating from B-AMN to VDM-SL

The main difficulty of the translation integration of B and VDM is in translating the structuring mechanisms of B-AMN to VDM-SL. Its type, expression and substitution language is, to within first approximation, a subset of VDM's and can be translated directly². We therefore focus on the translation of structuring.

The general approach is to translate each machine, except the top level machine, to a record with a field for each state variable. The top-level machine is translated to the VDM state with components for the included machines as well as for variables.

There are several structuring mechanisms in B which allow different degrees of hiding. We consider each of these in turn.

The Includes Clause. Machine inclusion is the major structuring mechanism for machines with state. It utilises a *semi-hiding* principle which allows the state of the included machine to be visible to the including machine, but only modified via its own operations. Each machine can only be included once in any other. This means that there can only exist one copy of a machine state in a hierarchy. For example, if a machine *C* includes a machine *B* and *B* includes a machine *A* then *C* cannot also include *A* explicitly, since *A* is included via *B*, and from *C* the state of *A* can only be accessed via the operations of *B*. (On the other hand, the same machine may be “seen” or “used” multiple times; see later.)

We can model the includes clause by using an extra field in the VDM record types. The state of the included machine becomes a field in the state of the including machine. Consider for example three machines *X*, *Y* and *Z*. Assume *X* includes *Y* and *Y* includes *Z*, while *Z* does not include other machines. The state of the three machines are represented using records. The “basic” machine *Z* is represented by:

$$\begin{array}{l} Z :: z1 : Z1 \\ \quad z2 : Z2 \end{array}$$

Y inherits *Z* so it must have access to *Z* state variables, e.g. in its invariant. Therefore *Z* is an extra field in *Y*'s record representation:

$$\begin{array}{l} Y :: z : Z \\ \quad y1 : Y1 \\ \quad y2 : Y2 \end{array}$$

X inherits *Y* so we get:

$$\begin{array}{l} X :: y : Y \\ \quad x1 : X1 \\ \quad x2 : X2 \end{array}$$

X now has access to *Z* via *Y*, so the transitivity is captured.

Next, consider B operations associated with machines. We represent these as functions in VDM-SL with extra arguments and results for before and after states. For example an operation of the machine *Z* is parameterised with the record type *Z* e.g.

$$opZ: args * Z \rightarrow res * Z.$$

² A notable exception is B's parallel substitution which updates two variables simultaneously. However, this can be modelled in VDM using a let statement to calculate the two new values before doing the updates.

An operation from machine X , opX , may call an operation in Y which is represented as follows (the μ operator modifies the named field of the given record type value with the given value):

```

let  $newy = opY(\dots, xstate.y)$ 
in
   $\mu(xstate, y \mapsto newy)$ 

```

In turn opY may manipulate the state variables of Z via a call to opZ . However, this does not influence the translation of opX .

The Sees Clause. The sees clause is more restricted than the includes clause. If a machine X sees a machine Y then X can read the variables of Y in its operations, but not in its invariant. It cannot write the variables and cannot call operations of Y . This means that Y does not need to be an extra field of the machine record for X . It is enough to model it as an extra argument of operations. Thus we get:

$opX: args * Y \rightarrow res$

The Uses Clause. The uses clause is similar to the sees clause and yet very different on one essential point: variables of the used machine can be referred to in the invariant of the using machine. The used variables must therefore be included in the record type modelling the using machine, as in the representation of the includes clause. However, unlike the includes clause, the uses clause can be used in multiple machines and this introduces a problem of multiple copies in the VDM translation. For example, suppose that two machines $Y1$ and $Y2$ each use a machine Z . Then if a machine X is to include $Y1$, it must also include not only Z , but also all other machines that use it (in this case $Y2$). Consequently, the VDM record type for X will contain three copies of the record for Z (once directly, and twice indirectly via the records for $Y1$ and $Y2$). However, the B specification contains only one copy of Z . This can be resolved by specifying that these copies in the VDM record for X must always be identical, for example by adding equality clauses to the invariant of the including machine of the form

$zstate = y.zstate.$

However, since using machines cannot change the used state, we do not need to worry about preserving this part of the invariant in the VDM operations.

The used state variables are visible in operations of the using machine, but as mentioned above an operation of a using machine cannot change the state of the used machine. Moreover, used operations are not visible in using operations. Hence, in this respect the uses clause behaves like the sees clause and we could therefore copy the approach to translating the sees clause and extend the arguments of the using operations with an extra argument corresponding to the state of the used machine. However, this state is already available in the record of the using machine, so an extra argument is not necessary.

Generally we do not need to ensure that B restrictions on for example visibility with respect to the correct use of variables are satisfied in the VDM model. For example, although semi-hiding is lost in the translation, this loss is unimportant since B's restrictions on visibility will already have been checked within B and will be maintained by the translation.

Sets and Constants. Other components of machines are sets and constants. In B, these are defined in properties clauses and may be non-deterministic. Sets are

translated to both a new type and a value definitions, corresponding to the type of the set and the set of all elements of that type. Constants are represented as value definitions.

Guidelines for Translation. We can now present general guidelines for the translation of B into VDM. A B model is translated by working bottom-up, from basic machines with no “imports” towards the top level machine. State variables of non-top level machines become fields of a record type which has the same name as the machine. Trivial type machines such as `Bool.TYPE` just become types in VDM-SL, e.g. `bool`. Invariants of machines are translated to invariants of the record types. Initialisation is modelled using functions which call “init” functions of included machines.

Machine operations are represented as functions, where the machine state record is an extra argument and result. Parallel substitution in operations is handled using μ -expressions, which are used to update fields of a record in parallel.

B	VDM
MACHINE X	state X of
INCLUDES Y	$y : Y$
VARIABLES $x1, x2$	$x1 : X1$ $x2 : X2$
INVARIANT $x1 \in X1, x2 \in X2$	end
OPERATIONS $opX = \dots$	types
END	$Y :: y1 : Y1$ $y2 : Y2$
MACHINE Y	
SEES Z	
VARIABLES $y1, y2$	$Z :: z1 : Z1$ $z2 : Z2$
INVARIANT $y1 \in Y1, y2 \in Y2$	
OPERATIONS $opY = \dots$	operations
END	$opX () \dots$
MACHINE Z	
VARIABLES $z1, z2$	functions
INVARIANT $z1 \in Z1, z2 \in Z2$	$opY (yin : Y, zin : Z)$ $yout : Y \triangle$
END	$\dots$

Fig. 2. Summary of the translation from B to VDM.

For translating the top-level machine we use a VDM-SL state with an invariant and an initialisation predicate. Promoted operations become operations associated with the state by defining their body to call the lower-level operation.

Expressions in predicates are easy to translate since B’s expression language is roughly speaking a subset of VDM’s.

The translation is summarised in Fig. 2 which gives the translation of a representative partial specification in B and the equivalent translation in VDM.

In this figure, machines Y and Z are translated as record types. The operation opY is translated as a VDM function taking type Y as argument and result. Since machine Y sees Z , the record type Z is added as an argument to opY . The top-level machine X is used to define the VDM state model; this contains the (translations of the) variables of X together with a value of type Y (since machine X includes Y). The operation opX of machine X becomes an operation in the VDM specification.

4. Translating from VDM-SL to B-AMN

In translating from VDM-SL to B-AMN we have to consider, firstly, how to represent complex types and expressions within an impoverished expression syntax, and secondly, how to infer a structured state model from an unstructured model. This latter task requires the synthesis of a modular structure for the B specification from the type structure of the flat VDM specification. Further details on this synthesis are given in [MRB98].

Types and Expressions. It is possible to define a “reasonably literal” translation from VDM-SL to AMN, wherein type definitions, expressions and functions are translated as *property-oriented* (algebraic) definitions, and the (monolithic) top-level VDM-SL state definition and operations are translated to a single AMN machine.

To explain this approach, consider the state of a representative VDM specification:

```
state  $S$  of
   $n : \mathbb{N}$ 
   $a : A$ 
end
```

where A is a user defined record type:

```
 $A :: a1 : A1$ 
       $a2 : A2$ 
```

In the property oriented approach, since the record type A is translated as an algebraic specification, it is given as the following stateless machine (truncated for brevity):

MACHINE A_Type

SETS A

CONSTANTS

$mk_A, inv_A, a1, a2$

PROPERTIES

```
 $a1 : A \rightarrow A1 \wedge$ 
 $a2 : A \rightarrow A2 \wedge$ 
 $mk\_A : A1 \times A2 \rightarrow A \wedge$ 
 $inv\_A : A \rightarrow \text{BOOL} \wedge$ 
 $(\forall xx,yy). (xx \in A1 \wedge yy \in A1 \Rightarrow$ 
         $(a1(mk\_A(xx,yy)) = xx))$ 
```

...

END

And a top level state machine of the form:

MACHINE S

SEES $A.Type$

VARIABLES n, a

INVARIANT

$n \in \mathbb{N} \wedge a \in A$

END

This is a literal translation of the VDM, and takes a similar approach to the translation of Z types into B proposed in [RBH94]. The *algebraic* VDM record type A is translated into a stateless “property-oriented” machine, which declares the type as a set, a new mk_A constant as the constructor function, the fields as projection functions, and a new inv_A constant as the invariant function. The behaviour of these constants is defined using properties, in effect giving an algebraic specification of the type. The properties clause soon becomes very large, with complex first-order logic and set theory expressions. Because of the relative weakness of the expression language in B to that in VDM-SL, these become hard to read, and the support tools for B find such expressions hard to deal with.

However, there are reasonably obvious translations from the VDM expression syntax to AMN’s generalised substitutions. Though the latter are state transformers and not functional expressions, this suggests a translation approach that wherever possible “re-interprets” VDM functions as AMN operations that do not change the state.

Using the property oriented approach leads to a different “granularity” of the state than would be natural in a B specification. In normal usage, because of its flat state, VDM-SL uses record types for structuring data. On the other hand, because of its emphasis on generalised substitutions and primitive data types, AMN uses machines for structuring data.

In this paper We propose an approach to translation from VDM to B which attempts to cater for the differences in “state granularity” between VDM-SL and AMN. This translation synthesises a finer state structure from the VDM-SL record structure, using the most appropriate style of B specification for the various parts of the VDM specification, resulting in a specification with a more distributed state.

4.1. Preprocessing the VDM Specification

First, we analyse the state model of the VDM-SL specification in a top-down manner to determine which type definitions contribute to the state. The manner in which a type is used is significant: if the state contains only individual values of a type (however deeply-nested in the type hierarchy), then we say that this type usage is *simple* and translate to machines with state variables for each field in the type and whose operations behave similarly to VDM record functions. However, if the state contains sets, sequences or maps of values of a type, then we say that the usage is *complex* and translate using “object-manager” machines, in a style similar to that given in [Lan96]. Here the creation and use of multiple (state) instances of the record type are controlled by a manager machine for that type. Other types, such as record types which appear as (non-state) arguments or results of functions or operations, are handled as property-oriented definitions.

In this top-down analysis, the VDM spec is preprocessed to decide how to best translate each record type. Two sets are declared, *Simple* and *Manager* which represent those types which should be represented as a simple object machine, or as an object manager machine respectively. The analysis is a simple recursive procedure. First find the state, for example:

```
state Example of
  a : T           // where T contains no record type
  b : R           // where R is a record type
  c : S-set       // where S is a record type
end
```

T is any type which does not contain a record type, and it can be basic, user defined or an aggregate type (set, map or sequence) which do not have record types as members.

Any record types which are referenced directly, such as *R*, are added to the set *Simple*, and any record which is part of an aggregate, such as *S*, are added to the set *Manager*.

This process is repeated for each record type $R \in \text{Simple}$, and $S \in \text{Manager}$, with the additional conditions:

1. if $S \in \text{Manager}$, then $S \notin \text{Simple}$;
2. if record *R* occurs in a field of $S \in \text{Manager}$, then $R \in \text{Manager}$.

Thus if a record type *S* is added to *Manager*, it must be removed from *Simple*, and any records referenced from *S* must also be added to *Manager*.

4.2. Inferring a Structured Model

When the preprocessing is complete, then machines can be generated. All record types in *Simple* are translated as simple structured object machines, while types which are in *Manager* are translated as object manager machines. Any record types not in either of these sets are translated as property oriented stateless machines.

Thus there are three cases to consider of records to translate: a *Simple* record with a reference to a *Simple* record within it; a *Simple* record with a reference to a *Manager* record; and a *Manager* record with a reference to a *Manager* record. The final case of *Simple* within *Manager* will not occur.

In the first case, if for example, $P \in \text{Simple}$ such that:

```
P :: p1 : T           // non record type
      p2 : R           // record type such that R ∈ Simple
```

then we would generate the simple state machine:

MACHINE *P.Obj*

INCLUDE *p2.R.Obj*

VARIABLES

p1

INVARIANT

p1 ∈ *T*

END

Note that the machine R_Obj is included into this machine with a renaming, using the convenient name $p2$. This machine may well be used elsewhere in the specification, and each including machine needs a unique copy.

R_Obj is a *simple state* machine derived as follows. If:

$$R :: r1 : R1 \\ r2 : R2$$

In the translation, the record R is split into its fields, and give a state variable defined for each:

MACHINE R_Obj

VARIABLES

$r1, r2$

INVARIANT

$r1 \in R1 \wedge r2 \in R2$

...

END

The higher-level state machine P_Obj which includes this represents the “inheritance” of the datatype:

If the data types $R1, R2$ are themselves *Simple* or *Manager* record types they can be broken down further into similar machines. Thus we build a hierarchy of machines which preserve the structure of the VDM specification, but have a finer state granularity. This specification is much clearer and easy to work with, exploiting as it does the strength of B and B tools in manipulating machine state and generalised substitutions.

For the second case, if $P \in Simple$ such that:

$$P :: p1 : T \quad // \text{ non record type} \\ p2 : S \quad // \text{ record type such that } S \in Manager$$

then generate the simple state machine:

MACHINE P_Obj

INCLUDE S_Mgr

VARIABLES

$p1, p2$

INVARIANT

$p1 \in T \wedge p2 \in Sids$

...

END

In this case S_Mgr is an *Pobject manager* machine for the type S , as follows. If

$$S :: s1 : S1 \\ s2 : S2$$

then we translate this as:

MACHINE S_Mgr

SETS S_Ids

VARIABLES

$sids, s1, s2$

INVARIANT

$sids \subseteq S_Ids \wedge$

$s1 \in sides \rightarrow S1 \wedge$

$s2 \in sides \rightarrow S2$

...

END

Typically, an object manager machine will also include some basic operations for inspecting and manipulating the variables; for example equality should be defined on the value of the attributes rather than on the identifier. In this paper, these are omitted for clarity.

Thus using an object manager machine, aggregates can be formed and manipulated. Note that there is no renaming carried out here. There is only one object manager machine in the system, and all references should be to that machine. However, there is an issue here: the rules of composition in B allow a machine to be included in only one other machine. Thus if the manager record is referred to from more than one record type, this condition may be broken. The resolution of this problem would be to break down the S_Mgr machine into two, with a simple machine declaring the abstract set S_Ids , representing the object identifiers, and a manager machine. The manager machine is then included with renaming, and the set is accessed via the SEES construct. This allows the same set of object identifiers to be used across different object managers.

For the third case, if $P \in Manager$ such that:

$$\begin{array}{ll} P :: r1 : T & // \text{ non record type} \\ r2 : S & // \text{ record type such that } S \in Manager \end{array}$$

then generate the object manager machine as follows, which includes a further object manager machine S_Mgr .

MACHINE P_Mgr

INCLUDE S_Mgr

SETS P_Id

VARIABLES

$pids, r1, r2$

INVARIANT

$pids \subseteq P_Id \wedge$

$r1 \in pids \rightarrow T \wedge$

$r2 \in pids \rightarrow sides$

...

END

Other types and record types, which are not accessed via the state model are treated by a property oriented translation.

It may also be necessary to give property oriented translations as well as state based ones for certain records; they are used as input/output to functions for example. The analysis of the specification can be extended to cover this eventuality.

The translation presented so far concentrates on the different data models of VDM and B. To present a full translation, other aspects of the languages need to be considered, especially the type and expression language, and the operation and function language, which is beyond the topic of this paper.

5. A Worked Example

To illustrate the different approaches, we consider the following small example of a VDM-SL specification taken from a SPECTRUM user scenario concerning the management of the doors on metro trains.

This example was initially designed using OMT from which a VDM specification was derived. The fragment given here has a state *Metro*, with a train component. The train itself is a record with two components, *motion*, representing the status of the train's motion, and the current speed of the train. The invariant on the train states that when the train is stopped, its speed is zero. We also provide a function for braking.

```
state Metro of
  train : Train
end

Train :: motion : MOTIONSTATUS
      speed :  $\mathbb{N}$ 

inv mk-Train (mm, ss)  $\triangle$ 
  (mm = STOPPED  $\Rightarrow$  ss = 0)

brake (tin : Train) tout : Train
pre  tin.motion  $\in$  {ACCELERATING, STEADY}
post tout = mk-Train (DECELERATING, tin.speed) ;
```

Under the property oriented translation, this becomes two machines, one with the state model:

```
MACHINE  Metro_Type
SEES
  Train_Type
VARIABLES
  train
INVARIANT
  train  $\in$  Train
END
```

The other machine is a stateless property-oriented specification, with the invariant represented as a complex first-order logic formula in the properties clause, and the *brake* represented as a stateless operation:

```
MACHINE  Train_Type
SETS Train0
```

CONSTANTS

Train, *mk_Train*, *inv_Train*, *motion*, *speed*, *init_Train*

PROPERTIES

$Train \subseteq Train0 \wedge$
 $mk_Train \in MOTIONSTATUS \times \mathbb{N} \rightarrow Train0 \wedge$
 $inv_Train \in Train0 \rightarrow BOOL \wedge$
 $motion \in Train0 \rightarrow MOTIONSTATUS \wedge$
 $speed \in Train0 \rightarrow \mathbb{N} \wedge$
 $(\forall mm,ss).(mm \in MOTIONSTATUS \wedge ss \in \mathbb{N} \Rightarrow$
 $(inv_Train(mk_Train(mm,ss)) \Leftrightarrow ((mm = stopped) \Rightarrow (ss = 0)))) \wedge$
 $\dots$

OPERATIONS

$tout \leftarrow brake(tin) \quad \widehat{=}$
PRE
 $tin \in Train \wedge$
 $motion(tin) \in \{ accelerating, steady \}$
THEN
 $tout := mk_Train(decelerating, speed(tin))$
END

END

In this latter machine, functions are represented as stateless operations, which permits a more expressive syntax than translating them as properties. Nevertheless, this is an awkward machine to manipulate in the B-Method, and while perfectly valid in the language, is not a “natural” approach in B.

However, using the synthesis method, after an analysis which determines that the train record type is a *Simple* type, it is translated into a machine with state variables.

MACHINE *Train_Obj*

VARIABLES

motion, *speed*

INVARIANT

$motion \in MOTIONSTATUS \wedge$
 $speed \in \mathbb{N} \wedge$
 $(motion = stopped) \Rightarrow (speed = 0)$

OPERATIONS

$brake \quad \widehat{=}$
PRE
 $motion \in \{ accelerating, steady \}$
THEN
 $motion := decelerating$
END

END

This machine is then “included” into the top-level Metro specification, with a renaming. Metro is otherwise the same as in the property oriented approach. This is a much more natural style in B using more state variables of simple types. This

machine can be easily included into a continuing B development and resulting proof obligations more easily expressed and discharged.

In effect, the proposed translation automates the extraction of *design information* from the VDM-SL specification, by deriving a finer-grained state model. Design is an intelligent process, and inevitably this design information may not be exactly as the user intended; an element of user supervision may be required here to judge whether the automatic design is suitable. However, as this is automatically generated, this useful structuring can be gained at low cost.

A useful test was the application of the B-AMN to VDM-SL translation given earlier to this latter specification. It produced a VDM specification very similar to the original, supporting our claim that the translations given here have a high degree of symmetry.

The definition of the translation is not yet complete. Some work is still required to provide a complete account of translating VDM functions and operations, and VDM full type and expression language needs to be tackled. Nevertheless, this approach seems to be promising, practical and useful.

6. Conclusion

A prerequisite of the benefits to be gained from heterogeneous development using VDM and B is a smooth integration of the methods which maintains the correctness of the development while adding little or no cost. The reported project demonstrated the feasibility of combining the two methodologies, and their supporting toolkits. In particular it explored the translations between the two notations. The translation of B-AMN to VDM-SL was shown to be a more straightforward task than the translation from VDM-SL to B-AMN, although ultimately, both are feasible.

The proposed VDM to B and B to VDM translations are largely symmetric. The translation from B-AMN to VDM-SL involves the loss of state structuring and its replacement with richer type structure using a bottom-up analysis of the specification. The translation from VDM-SL to B-AMN, which replaces mathematical expressiveness in the type system with design in the machine structure, reflects B's approach of being close to real machine types. The required machine structure can be largely inferred automatically by a top down analysis of the VDM and thus an automatic translator could really be seen as adding value to the source specification.

The translation automates the extraction of *design information* from the VDM-SL specification, by deriving a finer-grained state model. As the design process requires intelligent insight, the resultant design may not be in the form the user desires, and therefore an element of user judgement is still required to determine which elements of this design are appropriate. However, as the design elements have been automatically generated, the useful elements have been gained at low cost.

Thus the SPECTRUM project has advanced the understanding of the technical issues involved in the integration of VDM and B and the approach enabled by these translations yields the possibility of a formal development offering the advantages of both VDM and B and their respective tools. Each method can then be used in the lifecycle at those points for which it is most appropriate.

This work is not yet complete and further research is needed before support for such translations can be developed. The translations have been derived through

experience of the notations and have not been presented fully formally, nor have they been justified formally with respect the semantics of the two notations. VDM has a denotational semantics over a logic for partial functions and B has a weakest precondition semantics over classical logic. A formal proof of the preservation of semantics in the translations would require a mapping between the semantic models similar to that given in the weakest precondition semantics for Z in [CaW98]. However, in this case, the difference between the logics adds an extra concern. Recent developments in B, such as hypersubstitutions [DuS96] and “well-defined B” [BBM98] may aid semantic compatibility here. An investigation into the formal relationship between the methods is the subject of current research under the UK EPSRC funded project “VDM+B” which will investigate the semantic mapping necessary to underpin the translations presented here.

To date, the penetration of formal methods into mainstream software development has been extremely slight. One reason for this might be that the confusion amongst users concerning which methods are most appropriate for which applications does not encourage the take up of formal techniques in general. In bringing together the methods and tools for VDM and B the SPECTRUM project should also help to bring together their user communities and hence provide increasing evidence of the feasibility of the formal approach.

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