A Machine-Checked Proof for a Translation of Event-B Machines to JML

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Abstract. We present a machine-checked soundness proof of a translation of Event-B to the Java Modeling Language (JML). The translation is based on an operator $\text{EB2Jml}$ that maps Event-B events to JML method specifications, and deterministic and non-deterministic assignments to JML method post-conditions. This translation has previously been implemented as the EventB2Jml tool. We adopted a taking our own medicine approach in the formalisation of our proof so that Event-B as well as JML are formalised in Event-B and the proof is discharged with the Rodin platform. Hence, for any Event-B substitution (whether an event or an assignment) and for the JML method specification obtained by applying EventB2Jml to the substitution, we prove that the semantics of the JML method specification is simulated by the semantics of the substitution. Therefore, the JML specification obtained as translation from the Event-B substitution is a refinement of the substitution. Our proof includes invariants and the standard Event-B initialising event, but it does not include full machines or Event-B contexts. We assume that the semantics of JML and Event-B operate both on the same initial and final states, and we justify our assumption.

Keywords: Event-B, JML, EventB2Jml, Formal Proof, Translation, Rodin

1 Introduction

In an earlier work [14], we have proposed a design methodology that combines the use of design-by-contract techniques with JML [36,29,33] and correctness-by-construction techniques with Event-B [1]. In the proposed methodology, software development starts with a model in Event-B which is proven to adhere to a set of safety properties; the Event-B model is then refined, e.g. more details are added to the model, and the EventB2Jml tool [4] is used to translate the refined Event-B model to a JML specification. The EventB2Jml tool has been used to

4 Available at http://poporo.uma.pt/~ncatano/Projects/favas/EventB2JML.html
develop several Android applications, including a social-event planner and a car racing game. The translation from Event-B to JML is based on an operator EB2Jml that maps Event-B events to JML method specifications. Several of the rules that define EB2Jml are presented in Section 4.

This paper presents a machine-checked soundness proof of the translation encoded by EB2Jml. We have adopted a taking our own medicine approach in the formalisation of the proof so that Event-B as well as JML are formalised in Event-B and the proof is discharged in Rodin. Our formalisation rests on a shallow embedding of the semantics of Event-B and JML in the logic of the Event-B language. A shallow embedding approach (as opposed to a deep embedding) facilitates conducting and discharging a proof, but does not permit proofs of meta-properties about the language one is modelling. Hence, for any Event-B substitution (whether an event or an assignment) and for the JML method specification obtained by applying EventB2Jml to the substitution, we prove that the semantics of the JML method specification is simulated by the semantics of the substitution. In this respect, the semantics of the JML specification is a refinement of the semantics of the Event-B model in that any behaviour in JML is matched by a behaviour in Event-B. The soundness proof considers Event-B machine invariants, machine variables, events and, in particular, the Event-B initialising event, but not machines or machine contexts. To facilitate the proof we make a few assumptions (e.g. that the JML and Event-B models operate on the same initial and final states), and we justify the soundness of our assumptions. The proof is structured as a collection of contexts in Rodin with translation and semantic rules implemented as axioms. We used the ProB model-checker to find a valuation for our axiomatic definitions so as to enhance our confidence that no inconsistencies have been introduced.

The contributions of this paper are the following: (i.) we present a machine-checked soundness proof for the key rules defining the EB2Jml operator. These rules are the core of the implementation of the EventB2Jml tool. (ii.) we generalise our proof approach so that it can be extended to soundness proofs of translations of other formal languages.

2 Related Work

Defining a shallow or a deep embedding of one language in another is not a new idea. Indeed, J. Bowen and M. Gordon in propose a shallow embedding for Z in HOL. Catherine Dubois et al. propose a deep embedding of B in the logic of Coq for which B proof rules are formalized and proved correct. Jean Paul Bodeveix, Mamoun Filali, and César Muñoz generalise the substitution mechanism of the B method in Coq and PVS as a shallow embedding. In this current work, we consider a shallow embedding of Event-B (the successor of B) into Event-B itself, which allows us to use Rodin in proving the soundness of our translation.

Some other efforts relate to the automated verification of B and Event-B proof obligations. David Déharbe presents an approach to translate a particular
subclass of B and Event-B proof obligations into the input language of SMT-solvers [17]. We have implemented the EventB2Dafny Rodin plug-in [12] which translates Event-B proof obligations into Dafny, one of the front-end specification languages of the Boogie 2 tool [2].

Other works relate to the translation of formal specification (and modelling) languages, and to the implementation of tools automating these translations. In an earlier work [15], the authors define a translation from classical B to JML implemented in the ABTools suite [4].

Méry and Singh [32] define a translation tool (implemented as a Rodin plug-in) that automatically translates Event-B machines into several different languages: C, C++, Java and C#. Wright [40] defines a B2C extension to the Rodin platform that translates Event-B models into C code. However, this work considers only simple translations of formal concrete machines. Edmunds and Butler [19,20] present a tasking extension for Event-B that generates code for concurrent programs (targeting multitasking, embedded and real-time systems). The main issue with these tools is that the user has to provide a final (or at least an advanced) refinement of the system so that it can be directly translated to code. And, they are limited to integer and boolean types, so event guards cannot include relations or sets.

Jin and Yang [27] outline an approach for translating VDM-SL to JML. Their reasons for doing so are similar to our motivation for translating Event-B to JML – they view VDM-SL as a better language for modelling at an abstract level (much the way that we view Event-B), and JML as a better language for working closer to an implementation level. Bouquet et. al. have defined a translation from JML to B [6] and implemented their approach in the JML2B tool [7]. Their motivation is again quite similar to ours – they view translation as a way to gain access to more appropriate tools for the task at hand, which in this case is verifying the correctness of an abstract model without regard to code. JML verification tools are primarily concerned with verifying the correctness of code with respect to specifications, while B has much stronger tool support for verifying models.

3 Preliminaries

3.1 The Event-B Method

Event-B models are composed of machines and contexts. Machines contain the dynamic parts of a model (e.g. variables, invariants, events). Contexts contain the static part of a model (e.g. carrier sets, constants). Three basic relationships are used to structure a model. A machine sees a context and can refine another machine, and a context can extend another context. A partial example of a social networking model (adapted from the B model in [13]) is depicted in Figure 1 (abstract and first refinement machines). Both machines see a context ctx1 (not shown) that defines carrier sets PERSON (the set of all possible people in the network) and CONTENTS (the set of all possible images, text, ... in the
network). The abstract machine declares variables persons (the set of people actually in the network), contents (the set of content actually in the network), owner (a total surjection mapping each content item to its owner), and pages (a total relation indicating which content items are visible to which people). Invariant inv5 ensures that each content item is visible to its owner. Event-B provides notations $\leftrightarrow$ for a relation, $\rightarrow$ for a total surjective function, and $\leftrightarrow\leftrightarrow$ for a total surjective relation.

The initialisation event ensures that all of these sets, functions and relations are initially empty. The symbol $\emptyset$ represents the empty set. The abstract machine further defines the “standard” event create_account that adds a new person and associated initial content to the network. Event-B events can be executed/triggered when their guards (the part after the where) are true. Hence, the create_account event can execute whenever there is at least one person and at least one content item that has not yet been added. The meaning of an event is the meaning of the actions in its body (the part after the then). After the create_account event executes, the person $p_1$ and content $c_1$ are added to the network, $p_1$ owns $c_1$, and $c_1$ is visible to $p_1$.

The edit_owned event replaces a content item $c_1$ with a new content item newc with the same ownership and visibility. The symbol $\setminus$ represents set difference, $\mapsto$ a pair of elements, $\ll$ domain subtraction, which removes from a relation all the pairs with a first element in some set, and $\times$ cross-product. The expression $\text{pages}[\{c_1\}]$ evaluates the relation pages on the set $\{c_1\}$.

The first refinement of this machine (right Figure 1) introduces permissions. It adds variables viewp and editp which respectively track which people have permission to view and edit each content item (actions actr1 and actr2). The invariants further specify actions stating that the owner always has permission to view and edit an item, that a person must have view permission on an item in order to have edit permission, and that an item is not visible to a person who does not have view permission on the item. The abstract event create_account is extended so that the owner has edit and view permissions on the item, and edit_owned is extended so that the new content item has the same edit and view permissions as the item it is replacing.

3.2 JML

JML [16] is a model-based language designed for specifying the interfaces of Java classes. JML specifications are typically embedded directly into Java class implementations using special comment markers /*@ ... */ or //@. Specifications include various forms of invariants and pre- and post-conditions for methods. Mathematical types that are heavily used in other model based specification languages (sets, sequences, relations and functions) are provided in JML as classes.

Figure 2 presents a partial output of applying the EventB2Jml tool to the first refinement machine of the social networking system model (right Figure 1). In JML, model fields are specification-only – they are an abstraction of the mutable part of an object’s state, and need not be directly present in the implementation.
Fig. 1. Part of an Event-B machine for social networking (left: abstract machine. right: first refinement).
import poporo.models.JML.*;
import org.jmlspecs.models.JMLEqualsEqualsPair;

public abstract class ref1_permissions {

/*@ public model BSet<Integer> CONTENTS; */
/*@ public model BSet<Integer> PERSON; */

/*@ public model BSet<Integer> contents;
public model BRelation<Integer,Integer> editp;
public model BRelation<Integer,Integer> owner;
public model BRelation<Integer,Integer> pages;
public model BSet<Integer> persons;
public model BRelation<Integer,Integer> viewp; */

/*@ public invariant
persons.isSubset(PERSON) && contents.isSubset(CONTENTS)
&& owner.isaFunction() && owner.domain().equals(contents)
&& owner.range().equals(persons)
&& pages.domain().equals(contents) && pages.range().equals(persons)
&& owner.isSubset(pages)
&& viewp.domain().isSubset(contents) && viewp.range().isSubset(persons)
&& owner.isSubset(viewp) && owner.isSubset(editp)
&& editp.isSubset(viewp) && pages.isSubset(viewp); */

/*@ initially
persons.isEmpty() && contents.isEmpty() && owner.isEmpty()
&& pages.isEmpty() && viewp.isEmpty() && editp.isEmpty() ; */

/*@ assignable \nothing;
ensures \result <=>
(\exists Integer c1; (\exists Integer p1; (\exists Integer newc;
(old(contents.has(c1) && persons.has(p1) && owner.apply(c1) == p1
&& CONTENTS.difference(contents).has(newc)))));
public abstract boolean guard_edit_owned();

/*@ requires guard_edit_owned();
assignable contents, pages, owner, viewp, editp;
ensures (\exists Integer c1; (\exists Integer p1; (\exists Integer newc;
\old(contents.has(c1) && persons.has(p1) && owner.apply(c1) == p1
&& CONTENTS.difference(contents).has(newc))
&& contents.equals(\old(contents.difference(
new BSet<Integer>(c1)).union(new BSet<Integer>(newc)))))
&& pages.equals(\old(pages.domainSubtraction(
new BSet<Integer>(c1)).union(.Utils.cross(new BSet<Integer>(newc),
pages.image(new BSet<Integer>(c1))))))
&& owner.equals(\old(owner.domainSubtraction(new BSet<Integer>(c1)).union( 
new BRelation<Integer,Integer>(new JMLEqualsEqualsPair<Integer,Integer>
(newc,p1))))))
&& viewp.equals(\old(viewp.domainSubtraction(new BSet<Integer>(c1)).union( 
Utils.cross(new BSet<Integer>(newc),viewp.image(new BSet<Integer>(c1))))))
&& editp.equals(\old(editp.domainSubtraction((new BSet<Integer>(c1)).union( 
new BRelation<Integer,Integer>(new JMLEqualsEqualsPair<Integer,Integer>
(newc,p1))))));

also
requires !guard_edit_owned();
assignable \nothing;
ensures true; */
public abstract void run_edit_owned();
}
Classes \texttt{BSet} and \texttt{BRelation} are built-in to EventB2Jml and represent mathematical sets and relations, respectively. Event-B carrier sets are represented in JML as a set of integers (as instances of \texttt{BSet<Integer>}). The \texttt{model} fields are translations of the variables of the Event-B model in Figure 1 and have the same meanings as those variables. The \texttt{invariant} states properties that must hold in every visible system state – specifically before a public method is triggered and after the method terminates. This is semantically equivalent to conjoining the invariant to the pre- and post-conditions of each method specification.

In this example, the first part of the invariant corresponds to the invariant of the abstract model (see left Figure 1). In the Event-B model, \texttt{owner} is represented as a function, not as a relation. The invariant uses the method \texttt{isaFunction()} to enforce both that \texttt{owner} is a function and that its domain and range are \texttt{contents} and \texttt{persons} (respectively), thus defining \texttt{owner} as a total surjection.

The \texttt{initially} clause (which is implicitly conjoined to the post-condition of every constructor) specifies that all of the fields representing Event-B variables are initially empty. The values set by the \texttt{initially} clause are used as the initial values for checking class invariants.

An Event-B event can be triggered (its actions can be executed) when its guard is satisfied. This behaviour is modelled by creating two methods: a “guard” method containing the translation of the guard, and a “run” method containing the translation of the event body. In the “guard” method, \texttt{\result} represents the result returned by a method call. The “run” method should only be executed when the “guard” method returns \texttt{true}. In system states that satisfy the translation of the event guard, executing the “run” method must result in a state that satisfies the translation of the body. In system states that do not satisfy the translation of the event guard, the corresponding event could not be triggered and so executing the “run” method must have no effect. This is handled by translating an event to two JML method specification cases – one where the translation of the guard is satisfied, and one where it is not. This is expressed in the pre-condition (\texttt{requires} clause in JML) of each specification case. The first specification case for \texttt{run\_edit\_owned} (in which method \texttt{guard\_edit\_owned} returns \texttt{true}) specifies the effect of replacing a content item in the system. The \texttt{assignable} clause is a frame condition specifying what locations may change from the pre-state to the post-state, e.g. all fields representing Event-B variables for this case. The pre-state is the state on entry to the method and the post-state is the state on exit from the method. Two special \texttt{assignable} specification exist, \texttt{assignable \nothing}, which specifies that the method modifies no location, and \texttt{assignable \everything}, which specifies that the method can modify any. The post-condition (\texttt{ensures} in JML) is expressing that in the state on exit from the method, content item \texttt{c1} is replaced by content item \texttt{newc} with the same ownership, visibility and permissions. Expressions within \texttt{\old} are evaluated in the pre-state, while all other expressions are evaluated in the post-state. In the second specification case, no locations are \texttt{assignable}, and so the post-state must be equal to the pre-state when \texttt{guard\_edit\_owned} returns \texttt{false} in
4 The Translation from Event-B to JML

The translation from Event-B to JML is defined with the aid of an EB2Jml operator that translates Event-B syntax to JML syntax. In the following, we present the EB2Jml rules for Event-B substitutions and for the translation of a machine that are needed for the soundness proof in Section 5. A much more complete description of the translation is presented in [14].

Events in Event-B are translated to two JML methods: a guard method that determines when the guard of the corresponding event holds, and a run method that models the execution of the corresponding event. In Rule Any below, variables bound by an any construct are existentially quantified in the translation, as any values for those variables that satisfy the guards can be chosen. The Pred operator translates Event-B predicates and expressions to JML, so the guard method returns true when the translation of the guard is satisfied.

The JML specification of each run method uses two specification cases (indicated by keyword also in JML). In the first case, the translation of the guard is satisfied and the post-state of the method must satisfy the translation of the actions. In the second case, the translation of the guard is not satisfied, and the method is not allowed to modify any fields, ensuring that the post-state is the same as the pre-state. This matches the semantics of Event-B – if the guard of an event is not satisfied, the event cannot execute and hence cannot modify the system state. The translation of the guard is included in the post-condition of the first specification case of the run method in order to bind the variables introduced by the any, as they can be used in the body of the event. Translation of events uses an additional helper operator Mod, which calculates the set of variables assigned by the actions of an event (the JML assignable clause).

Note that the effective pre-condition of a JML method with multiple specification cases is the disjunction of the pre-conditions of each case – so that in our translation, the pre-condition of a run method is always true. Hence, even though guards are translated as pre-conditions, no method in the translation result has a pre-condition. Rather, the translation of the guard determines which behaviour the method must exhibit. The semantics of multiple specification cases in JML is implication – the post-state of a method must satisfy the post-condition (ensures clause) of a specification case only when the requires clause of that specification case holds.
The translation of ordinary and non-deterministic assignments via operator \texttt{EB2Jml} is presented below. The symbol \texttt{:|} represents non-deterministic assignment. Non-deterministic assignments generalise deterministic assignments (formed with the aid of \texttt{:=}), e.g. \texttt{v := v + w} can be expressed as \texttt{v :| v' = v + w}. If variable \texttt{v} is of a primitive type, the translation would use \texttt{==} rather than the \texttt{equals} method.

\[
\text{Pred}(E(s, c, v)) = E
\]

\[
\text{EB2Jml}(v := E) = v.\text{equals}(\text{old}(E))
\]

\[
\text{Pred}(P(s, c, v, v')) = P \quad \text{TypeOf}(v) = \text{Type}
\]

\[
\text{EB2Jml}(v :| P) = (\exists \text{Type } v'; \text{old}(P) \&\& v.\text{equals}(v'))
\]

Multiple actions in the body of an event are translated individually and the results are conjoined. For example, a pair of actions:

\[
\begin{align*}
\text{act1} \quad & x := y \\
\text{act2} \quad & y := x
\end{align*}
\]

is translated to: \texttt{x == old(y) \&\& y == old(x)} for integer variables \texttt{x} and \texttt{y}, which correctly models simultaneous actions as required by the semantics of Event-B.

The \texttt{Mod} operator \textit{collects} the variables assigned by Event-B actions. The cases of \texttt{Mod} for assignments are shown below. For the body of an event, \texttt{Mod} is calculated by unioning the variables assigned by all contained actions.

\[
\text{Mod}(v := E) = \{v\} \quad \text{Mod}(v :| P) = \{v\}
\]
Rule \textbf{Inv} translates a JML invariant to an Event-B invariant using the \textbf{Pred} operator.

\[
\text{Pred}(I(s, c, v)) = I
\]

\[
\text{EB2Jml(invariants } I(s, c, v)) =
\]

//@ public invariant I;

Rule \textbf{M} below translates a machine \textbf{M} that sees a context \textbf{C}. We assume that all Event-B proof obligations are discharged (e.g. in Rodin) before the machine is translated to JML, so that proof obligations and closely related Event-B constructs (namely, \textit{witnesses} and \textit{variants}) need not be considered in the translation and in the soundness proof. A \textit{witness} contains the value of a disappearing abstract event variable, and a \textit{variant} is an expression that should be decreased by all \textit{convergent} events. An Event-B machine is translated to a single \textbf{abstract} JML annotated Java class, which can be extended by a subclass that implements the abstract methods. The translation of the context \textbf{C} is incorporated into the translation of machines that see the context.

\[
\text{EB2Jml(sets } s) = S
\]
\[
\text{EB2Jml/constants } c) = C
\]
\[
\text{EB2Jml(axioms } X(s, c)) = X
\]
\[
\text{EB2Jml/theorems } T(s, c)) = T
\]
\[
\text{EB2Jml(variables } v) = V
\]
\[
\text{EB2Jml(invariants } I(s, c, v)) = I
\]
\[
\text{EB2Jml(events } e) = E
\]

context \textbf{C}
sets \textbf{s}
constants \textbf{c}
axioms \textbf{X(}s, c\text{)}
theorems \textbf{T(}s, c\text{)}
end

\[
\text{EB2Jml(machine } M \text{ sees } C')
\]
variables \textbf{v}
invariants \textbf{I(}s, c, v\text{)}
events \textbf{e}
end

\[
\text{public abstract class } M \{
S C X T V I E
\}
\]

The rules defining \textbf{EB2Jml} for sets, constants, axioms, theorems and variables are not needed for the proof (in the next section), and so are not presented here. The interested reader is invited to consult [14].

5 The Proof

Embedding a language in the logic of a proof assistant consists of encoding the semantics and syntax of the language in the logic. Two different ways of formalising languages in logic have been proposed, namely, deep and shallow embedding [12][23]. In the deep embedding approach, the syntax and the semantics of the language are formalised in logic as structures, e.g. as data-types. It is thus possible to prove meta-theoretical properties of the language, but proofs
are usually cumbersome. In the shallow embedding approach, the language is embedded as types or logical predicates. Proofs become simpler, although one cannot then prove meta-theoretical properties of the language itself.

Our proof of the soundness of the translation from Event-B to JML rests as a shallow embedding of Event-B and JML in the logic of the Event-B language. The proof allows for deterministic and non-deterministic assignments, events (including the initialising event) and machine invariants. Contexts are not considered. Our embedding abstracts away the translation of Event-B predicates, and thus the correctness of the semantics of the whole translation assumes the correctness of the translation of these predicates. We abstract machine variables and events, that is, we consider machines to be composed of a single variable and a (non-initialising) single event. Our proof of soundness can be extended to consider a set of variables and a set of events, but we have not done so here. Therefore, the ability of Event-B to non-deterministically trigger enabled events is not part of the soundness proof (or of the translation presented in Section 4). In this respect, we prove that a JML specification is a refinement of an Event-B model and this proof is approached in a per-event basis just as refinement proof obligations are generated for Event-B in tools like Rodin [38]. Notice that our soundness proof need not include a proof of absence of deadlocks (the machine invariant entails the disjunction of the guards of the events) since we assume that all the proof obligations of the Event-B model are discharged before it is translated to JML.

Roughly speaking, our soundness proof ensures that any state transition step of the JML semantics of the translation of some Event-B construct into JML can be simulated by a state transition step of the Event-B semantics of that construct. All steps in the proof are modelled in Event-B and implemented in Rodin [11], a platform that provides support for writing and verifying Event-B models [37]. The soundness condition just described is stated as a theorem and proved interactively in Rodin. The whole proof structure is represented by a collection of contexts in Rodin, with translation rules and semantics implemented as axioms.

Substitutions are of two forms as described in Figure 3. The substitution on the left non-deterministically selects a value that satisfies the predicate \( P \) and assigns this value to \( v \). The symbol \( :|\) stands for non-deterministic assignment. The predicate \( P \) is a before-after predicate that depends on the value of the machine variables before (\( v \)) and after (\( v' \)) the assignment. The substitution in right Figure 3 (an event) is parameterised by an event variable \( x \). The event may only be executed (triggered) when the guard \( G \) holds. If so, the implementation of the event may select appropriate values for \( v, v' \) and \( x \) that make the before-after predicate \( Q \) true.

In formalising and conducting the proof of soundness of the translation from Event-B to JML, we assume the following:

1. Translating an Event-B predicate produces a JML predicate whose semantics is the same as that of the predicate it was translated from.
2. Translating an Event-B machine invariant produces a JML invariant whose semantics is the same as of the invariant it was translated from. This is a logical consequence of the previous assumption and Rule Inv as presented in Section 4.

3. States are defined in the same way in the semantics of both Event-B and JML – as partial functions from identifiers to values. We are abstracting the differences between values in Event-B and JML by assuming that all values are drawn from a single set Value.

4. Event-B machines are composed of a single machine variable, an initialising event, and a single standard event. Machines do not see any context. Additionally, we consider a simplified version of Event-B substitutions. Rule NAsg in Section 4 operates on the substitution in left Figure 3, and the substitution in right is a simplified version of the one on which Rule Any in Section 4 operates, namely, the body of the event in right Figure 3 consists of a single event action.

Our soundness proof proceeds via the following sequence of steps:

1. expressing Event-B and JML constructs as types in Event-B.
2. implementing the EventB2Jml translation rules as type transducer rules.
3. defining a semantics of Event-B types as state transducers.
4. defining a semantics of JML types as state transducers.
5. proving that the semantics of the JML translation of Event-B constructs is simulated by the Event-B semantics of those constructs.

5.1 The Types for Event-B and JML

For Event-B we define types BPredType and BSubsType, representing the type of a predicate and the type of a substitution (a non-deterministic assignment or an event), together with type constructors BPred for predicates, Assg for assignments, and Any for events as below. Additionally, we define a distinguished initialisation event constructor BInit that produces a substitution. To provide a uniform presentation, we assume that all predicates in Event-B involve three identifiers, hence the arity of the constructor BPred. Thus, predicates $P$ and $G$
in Figure 3 will actually be represented by $BPred(v, v', v')$ and $BPred(v, x, x)$, respectively. Variable $v'$ is the after-value of $v$. The substitution in left Figure 3 is written $Assg(v, v', BPred(v, v', v'))$, where $BPred(v, v', v')$ models the before-after predicate $P$. This non-deterministic substitution picks a value that satisfies $P$ and assigns it to $v$. In general, $BPred$ represents predicates involving three parameters as follows: the first parameter is the machine variable, the second is the after-value of that same variable, and the third is the local event variable. If the third parameter is missing, as is the case in the substitution in left Figure 3, then we take the third parameter as the second one; if the second one is missing, as in the case of an event guard, then we choose the second parameter to be equal to the third one.

\[
\begin{align*}
BPred & : Id \times Id \times Id \rightarrow BPredType \\
Assg & : Id \times Id \times BPredType \rightarrow BSubsType \\
Any & : Id \times BPredType \times Id \times Id \times BPredType \rightarrow BSubsType \\
BInit & : Id \times Id \times BPredType \rightarrow BSubsType
\end{align*}
\]

We use carrier types to abstract away unnecessary details in the Event-B to JML translation. Types defined for Event-B predicates, substitutions, and machines are the sets $BPredicate$, $BSubs$, and $BMachine$ respectively.

\[
\begin{align*}
\text{sets} & : BPredicate \; BSubs \; BMachine \\
\text{invariants} & : BPredType \subseteq BPredicate \\
& : BSubsType \subseteq BSubs \\
& : MachineType \subseteq BMachine
\end{align*}
\]

Types for JML constructs are defined in a similar way as for Event-B, but many more components are involved, e.g. we define $JmlNothing$ and $JmlEverything$ representing JML’s assignable specifications $\nothing$, the empty set, and $\everything$, the set of all the program identifiers.

\[
\begin{align*}
JmlNothing & \subseteq Id \\
JmlNothing & = \emptyset \\
JmlEverything & = Id
\end{align*}
\]

We consider JML predicate definitions involving,

- equality of identifiers, as in $x=y$
- existentially quantified predicates ($\exists x. \; T \; x; \ldots$)
- JML boolean operators $&&$ (logical and), $||$ (logical or)
- constant predicates $true$, $false$
- JML predicates with identifier values taken from the pre-state, as in $\old(P)$
- JML predicates with identifier values taken from the post-state (the default)

These types appear in the translation to JML of Event-B constructs. Hence, Event-B predicates are translated to semantically equivalent JML predicates,
non-deterministic assignments are translated to existentially quantified predicates (rule \texttt{NAsg} in Section 4), and events to JML specified methods (rule \texttt{Any} in Section 4). JML predicates appear in the \texttt{requires} (pre-condition) and \texttt{ensures} (post-condition) parts of JML-specified methods. For each predicate listed we define a type (a subset of \texttt{JmlPredicate}), e.g. \texttt{JmlExistsType}, \texttt{JmlAndType}, etc. and a type constructor. Type constructors are shown below. Notice that, as for Event-B predicates, a simple JML predicate represented by the \texttt{JmlPred} constructor involves exactly three identifiers. \texttt{JmlMeth} constructs a JML method specification from a JML normal (\texttt{JmlNormal}) and exceptional (\texttt{JmlExceptional}) behaviour specifications. Normal and exceptional specifications are composed of a pre-condition, a frame condition (the set of variables that may be modified), and a normal and exceptional post-condition, respectively. \texttt{JmlOld} matches the JML \texttt{\textbackslash old} operator, and \texttt{JmlBecomes} relates the value of machine variables in the pre-state with the value in the post-state.

\begin{verbatim}
JmlExists ∈ Id × JmlPredicate → JmlExistsType
JmlAnd ∈ JmlPredicate × JmlPredicate → JmlAndType
JmlTrue ∈ JmlTrueType
JmlFalse ∈ JmlFalseType
JmlBecomes ∈ Id × Id → JmlBecomesType
JmlNot ∈ JmlPredicate → JmlNotType
JmlOld ∈ JmlPredicate → JmlOldType
JmlPred ∈ Id × Id × Id → JmlPredType
JmlMeth ∈ JmlNormalType × JmlExceptionalType → JmlMethType
JmlNormal ∈ JmlPredicate × \mathcal{P}(Id) × JmlPredicate → JmlNormalType
JmlExceptional ∈ JmlPredicate × \mathcal{P}(Id) × JmlPredicate → JmlExceptionalType
\end{verbatim}

5.2 The Event-B to JML Translation Rules

The translation rules of Section 4 are modelled as total functions transforming Event-B types into JML types and predicates. We consider five functions: one for translating Event-B predicates, one for non-deterministic assignments, one for standard events, one for initialising events, and one for machine invariants. These functions are shown below. An Event-B predicate is transformed into a JML predicate, a non-deterministic assignment is transformed into a JML predicate that is used within a JML postcondition specification, a standard event becomes a JML method specification, an initialising event becomes the postcondition of a JML (Java) constructor, and an Event-B machine invariant is translated to a JML class invariant.

\begin{verbatim}
BPred2Jml ∈ BPredicate → JmlPredicate
Assg2Jml ∈ BSubs → JmlPredicate
Any2Jml ∈ BSubs → JmlMethType
BInit2Jml ∈ BPredicate → JmlPredicate
BInv2Jml ∈ BInvType → JmlPredicate
\end{verbatim}
The translation rules for Event-B substitutions (and other Event-B constructors) are expressed as axioms. Simple substitutions are presented in left Figure 3, where $P$ is a before-after predicate involving variables $v$ and $v'$. Since this substitution is not guarded (meaning there is no condition required for the substitution to be executed), its translation amounts to the translation of $P$, as shown by Rule NAsg in Section 4. This is expressed by the following axiom, where $BPred(v, v', v')$ models $P$, $JmlOld$ evaluates $P$ in the pre-state, and $JmlBecomes$ expresses how the value of the machine variable changes from the prestate to the poststate.

$$\forall v, v'. (v \in Id \land v' \in Id \Rightarrow 
\text{Assg2Jml}(\text{Assg}(v, v', BPred(v, v', v')))) = 
\text{JmlExists}(v', \text{JmlAnd}(\text{JmlOld}(BPred2Jml(BPred(v, v', v'))), 
\text{JmlBecomes}(v, v'))))$$

Rule Any in Page 9 formalises the translation of the event shown in Figure 3. The event implements a guarded substitution. The translation of the event includes a normal and an exceptional behaviour specification cases. If the guard of the event holds, the method may modify the machine variable $v$, and the post-condition of the method correctly implements the effect produced by the event ($JmlNormal$). If the guard of the event does not hold ($JmlExceptional$), the method is not allowed to modify any variable, and it produces no effect.

$$\forall v, v', x. (v \in Id \land v' \in Id \land x \in Id \Rightarrow 
\text{Any2Jml}(\text{Any}(x, BPred(v, x, x), v, v', BPred(v, v', x)))) = 
\text{JmlMeth}(\text{JmlNormal}(\text{JmlExists}(x, BPred2Jml(BPred(v, x, x))), 
\{v\}, 
\text{JmlExists}(x, \text{JmlAnd}(\text{JmlOld}(BPred2Jml(BPred(v, x, x))), 
\text{JmlExists}(v', \text{JmlAnd}(\text{JmlOld}(BPred2Jml(BPred(v, v', x))), 
\text{JmlBecomes}(v, v'))))))), 
\text{JmlExceptional}(\text{JmlNot}(\text{JmlExists}(x, BPred2Jml(BPred(v, x, x)))), 
\text{JmlNothing}, 
\text{JmlTrue}))$$

5.3 Semantics

Event-B and JML semantics are defined as state transition systems. Given any two states $a, b$ and an Event-B substitution $S$, we show that if the pair $(a, b)$ belongs to the state transition of the JML semantics of the translation of the type of $S$ ($MachineType$, $AssgType$, $AnyType$, etc) into JML, then $(a, b)$ also belongs
to the Event-B semantics of the type of $S$. We assume that state definitions in
the semantics of Event-B and in JML are both the same. For each construct in
Event-B and JML, we define a total function that holds whenever a given pair
of states represents a valid transition for that construct. Similarly, the semantics
of Event-B and JML predicates is given by a predicate in the semantic domain
that holds in a state whenever the B or JML predicate is true in that state. The
types involved in the definition of the Event-B semantic functions are shown next.
States are partial functions that map identifiers to values. Function $BPredSem$
provides a semantics for Event-B predicates, $BAssgSem$ for non-deterministic
assignments, $BAnySem$ for events, and $BInitSem$ for the initialising event.$BPredSem$
returns all the states in which the predicate holds, the other types
return a pair of states, the pre- and the post-states. The semantics of
$BAssgSem$, $BAnySem$, and $BInitSem$ depend on the machine invariant, represented as an
element of type $BPredicate$.

\[
\begin{align*}
\text{State} &= (Id \rightarrow Value) \\
BPredSem &\in BPredicate \rightarrow \mathbb{P}(State) \\
BAssgSem &\in BSubs \times BPredicate \rightarrow \mathbb{P}(State \leftrightarrow State) \\
BAnySem &\in BSubs \times BPredicate \rightarrow \mathbb{P}(State \leftrightarrow State) \\
BInitSem &\in BSubs \times BPredicate \rightarrow \mathbb{P}(State \leftrightarrow State)
\end{align*}
\]

A transition from state $a$ to state $b$ for the execution of the substitution in
left Figure 3 exists if and only if the machine invariant holds in $a$ and $b$, and
there exists some post-state value $y$ for $v'$ such that the predicate $P(v, y)$ holds
in state $a \Leftarrow \{(v', y)\}$, and the valuation of identifier $v$ in state $b$ is equal to $y$. The
symbol $\Leftarrow$ stands for relation overriding so that $a \Leftarrow \{(v', y)\}$ denotes the state
$a$ modified so that $a(v')$ is equal to $y$. This is asserted in the following axiom.

\[
\forall v, v', a, b. \ (v \in dom(a) \land v' \in Id \land v' \notin dom(a) \land v' \neq v \land a \in State \land b \in State \Rightarrow ( (a, b) \in BAssgSem(Assg(v, v', BPred(v, v', v')), BInv(v, v, v)) \\
\Leftarrow ( a \in BPredSem(BInv(v, v, v)) \land b \in BPredSem(BInv(v, v, v)) \land \exists y. ( y \in Value \land (a \Leftarrow \{(v', y)\}) \in BPredSem(BPred(v, v', v')) \land b = (a \Leftarrow \{(v, y)\}))
\)
\]

For the event in right Figure 3 a transition from state $a$ to state $b$ is valid
if only if (1) the machine invariant holds in $a$ and $b$, (2) the predicate $G(v, x)$
holds in a state $a$ that maps some value $y$ to variable $x$, and (3) there exists
some value $z$ for $v'$ such that $P(v, v', x)$ holds in state $a$ modified so that $v'$ has
value $z$ and $x$ has value $y$; otherwise (2) if the predicate $G(v, x)$ does not hold in
state \( a \), then states \( a \) and \( b \) are the same. \( BInitSem \) (which is not shown here) is defined similarly to \( BAssgSem \).

\[
\forall v, v', x, a, b. (v \in \text{dom}(a) \land v \in \text{dom}(b) \land v' \in \text{Id} \land v' \notin \text{dom}(a) \land v' \notin \text{dom}(b) \land x \in \text{Id} \land x \notin \text{dom}(a) \land x \neq v \land a \in \text{State} \land b \in \text{State} \Rightarrow
( (a, b) \in BAnySem(\text{Any}(x, B\text{Pred}(v, x, x), v, v', B\text{Pred}(v, v', x)), B\text{Inv}(v, v, v)) \leftrightarrow
( (a \in B\text{PredSem}(B\text{Inv}(v, v, v)) \land
b \in B\text{PredSem}(B\text{Inv}(v, v, v))) \land
( \exists y. (y \in \text{Value} \land (a \nless \{(x, y)\}) \in B\text{PredSem}(B\text{Pred}(v, x, x))) \land
\exists z. (z \in \text{Value} \land (a \nless \{(v', z)\}) \in B\text{PredSem}(B\text{Pred}(v, v', x))) \land
b = a \nless \{(x, y)\} \less \{(v, z)\})
) \lor
(\neg \exists y. (y \in \text{Value} \land (a \nless \{(x, y)\}) \in B\text{PredSem}(B\text{Pred}(v, x, x)) \land (a = b))
)
)
\]

As with the Event-B semantics, we define various total functions for JML constructs, e.g. predicates and method specifications, that hold for a pair of states when they represent a valid transition from the first state (the pre-state) to the second (the post-state). These functions and their types are presented below. \( JmlPredSem \) provides the semantics of a predicate in JML, \( JmlNormalSem \) and \( JmlExcSem \) the semantics of the normal and exceptional termination of a method, and \( JmlMethSem \) the semantics of a JML method specification. These last three constructs are parameterised by a JML invariant of type \( JmlPredicate \).

\[
\begin{align*}
JmlPredSem & \in JmlPredicate \rightarrow (\text{State} \leftrightarrow \text{State}) \\
JmlNormalSem & \in JmlNormalType \times JmlPredicate \rightarrow (\text{State} \leftrightarrow \text{State}) \\
JmlExcSem & \in JmlExceptionalType \times JmlPredicate \rightarrow (\text{State} \leftrightarrow \text{State}) \\
JmlMethSem & \in JmlMethType \times JmlPredicate \rightarrow (\text{State} \leftrightarrow \text{State})
\end{align*}
\]

The axiom below provides the semantics of \( JmlNormalSem \) for method pre-condition \( \text{req} \), method post-condition \( \text{ens} \), frame-condition \( \text{asg} \), and JML invariant \( \text{inv} \). The symbol \( \nless \) stands for domain restriction, hence the state “\( \text{Id} \nless \text{asg} \)" only maps elements in the domain “\( \text{Id} \nless \text{asg} \)”. The pair of states \( (a, b) \) are in the semantics of the normal behaviour specification of a method if \( a \) and \( b \) each adhere to the JML invariant, the method precondition - evaluated in the pre-state - implies the method post-condition, and \( a \) is equal to \( b \) except possibly for the variables in the set \( \text{asg} \). The semantics of \( JmlExcSem \) is defined similarly, and is not shown here.
∀ req, asg, ens, inv, a, b. ( a ∈ State ∧ b ∈ State ∧
  req ∈ JmlPredicate ∧ asg ⊆ Id ∧ ens ∈ JmlPredicate ∧ inv ∈ JmlPredicate ⇒
  ( (a, b) ∈ JmlNormalSem(JmlNormal(req, asg, ens), inv)
  ⇔
  ( (a, a) ∈ JmlPredSem(inv) ∧ (b, b) ∈ JmlPredSem(inv) ∧
    (Id \ asg) ⪯ a = (Id \ asg) ⪯ b
  ) ) )

The semantics of a JML method specification holds for a pre-state a and a post-state b if and only if the normal and exceptional behaviour specifications hold for the same states. This is shown by the axiom below.

∀ req1, req2, asg1, asg2, ens1, ens2, inv, a, b. ( a ∈ State ∧ b ∈ State ∧
  req1 ∈ JmlPredicate ∧ asg1 ⊆ Id ∧ ens1 ∈ JmlPredicate ∧
  req2 ∈ JmlPredicate ∧ asg2 ⊆ Id ∧ ens2 ∈ JmlPredicate ∧
  inv ∈ JmlPredicate ⇒
  ( (a, b) ∈ JmlMethSem(JmlMeth(
    JmlNormal(req1, asg1, ens1),
    JmlExceptional(req2, asg2, ens2)), inv)
  ⇔
  (a, a) ∈ JmlNormalSem(JmlNormal(req1, asg1, ens1), inv) ∧
  (a, b) ∈ JmlExcSem(JmlExceptional(req2, asg2, ens2), inv)
  ) )

JML predicates evaluated in a post-state b can refer to predicates evaluated in a pre-state a using the JML \old operator. How these states relate is best seen in the axiom below.

∀ p, a, b. ( a ∈ State ∧ b ∈ State ∧ p ∈ JmlPredicate ⇒
  ( (a, b) ∈ JmlPredSem(JmlOld(p))
  ⇔
  (a, a) ∈ JmlPredSem(p)
  ) )

The predicate JmlBecomes specifies how the value of a variable can change from the pre-state to the post-state of a method. JmlBecomes holds for a pair of states (a, b) whenever the post-state state b is the same as pre-state a with identifier v' removed and the value it had given to identifier v. That is, the value of variable v' in the pre-state is represented by the value of v in the post-state. The Event-B symbol ≪ is called domain subtraction, hence “{v'} ≪ a” removes
all the pairs from a whose first element is $v'$. The symbol $\triangleleft$ is the symbol for relation overriding introduced above, hence the state “$a \triangleleft \{ v, a(v') \}$” binds $v$ to $a(v')$.

\[
\forall v, v', a, b. \ (a \in \text{State} \land b \in \text{State} \land v \in \text{Id} \land v' \in \text{Id} \land\]
\[ v \in \text{dom}(b) \land v' \notin \text{dom}(b) \land v' \in \text{dom}(a) \land v \in \text{dom}(a) \land v' \neq v \Rightarrow\]
\[ (a, b) \in \text{JmlPredSem}(\text{JmlBecomes}(v, v')) \]
\[ \iff\]
\[ b = \{ v' \} \triangleleft (a \triangleleft \{ (v, a(v')) \}) \]
\]

The axiom for existentially quantified predicates is shown below. It says that $\text{JmlExists}(x, p)$ holds for a pre-state $a$ and a post-state $b$ if and only if $b$ includes $a$, $b$ binds $x$ to some value $y$, and it does not include any other binding, except for those that might be created within $p$.

\[
\forall x, p, a, b. \ \exists y. \ (a \in \text{State} \land b \in \text{State} \land x \in \text{Id} \land x \notin \text{dom}(a) \land y \in \text{Value} \land p \in \text{JmlPredicate} \ \Rightarrow\]
\[ (a, b) \in \text{JmlPredSem}(\text{JmlExists}(x, p)) \]
\[ \iff\]
\[ (a \triangleleft \{ (x, y) \}) \subset b \land a = (\text{dom}(a), b) \land\]
\[ ((a \triangleleft \{ (x, y) \}), b) \in \text{JmlPredSem}(p) \]
\]

The semantics of other JML boolean operators follows. The boolean operator $\text{JmlTrue}$ holds for any pair of states and $\text{JmlFalse}$ for none.

\[
\text{JmlPredSem}(\text{JmlTrue}) = \text{State} \times \text{State} \\
\text{JmlPredSem}(\text{JmlFalse}) = \emptyset
\]

### 5.4 The Proof Statement

The semantics of JML and Event-B relate as described in Figure 4 Hence, for any pair of states $(a, b)$, and for any JML method obtained via translation from an Event-B substitution (non-deterministic assignment or event), if the pair of states is an element of the semantics of the JML method, then it is also an element of the semantics of the Event-B substitution that was translated. We assume that translation of Event-B predicates to JML is correct. The expression of the relation shown in the figure is achieved through the theorem that follows. The function $\text{Any2Jml}$ produces an element of type $\text{JmlMethType}$. 
Theorem 1. The translation of an event is sound:

\[ \forall x, v, v', a, b. \ ( x \in Id \land v \in Id \land v' \in Id \land a \in State \land b \in State \land \\
\quad v \in \text{dom}(a) \land v \in \text{dom}(b) \land v' \notin \text{dom}(a) \land v' \notin \text{dom}(b) \land x \notin \text{dom}(a) \land \\
\quad v' \neq v \land x \neq v \land x \neq v' \Rightarrow \\
\quad (a, b) \in \text{JmlMethSem}(\text{Any2Jml}(\text{Any}(x, BPred(v, x, x), v, v', BPred(v, v', x))), \text{JmlInv}(v, v, v)) \\
\Rightarrow \\
\quad (a, b) \in \text{BAnySem}(\text{Any}(x, BPred(v, x, x), v, v', BPred(v, v', x)), \text{BInv}(v, v, v)) \]

Notice that we state a weak form of semantic correctness in the above theorem. As previously mentioned, we want to guarantee that any valid transition of the JML method produced by the translation must also be a valid transition of the source Event-B substitution. That is, an Event-B substitution must be capable of simulating any valid transition of its JML method counterpart. The JML translation then constitutes a sort of “refinement” of the Event-B specification.

The theorem above is discharged under the assumptions below. The translation of an Event-B predicate (machine invariant) on some given variables produces the same predicate (class invariant) as in JML.
∀t, u, z. ( t ∈ Id ∧ u ∈ Id ∧ z ∈ Id ⇒ BPred2Jml(BPred(t, u, z)) = JmlPred(t, u, z) )

∀t, u, z, s. ( t ∈ Id ∧ u ∈ Id ∧ z ∈ Id ∧ s ∈ State ⇒ JmlPredSem(JmlPred(t, u, z), s) = BPredSem(BPred(t, u, z), s) )

∀t, u, z. ( t ∈ Id ∧ u ∈ Id ∧ z ∈ Id ⇒ BInv2Jml(BInv(t, u, z)) = JmlInv(t, u, z) )

∀t, u, z, s. ( t ∈ Id ∧ u ∈ Id ∧ z ∈ Id ∧ s ∈ State ⇒ JmlPredSem(JmlInv(t, u, z), s) = BPredSem(BInv(t, u, z), s) )

The whole formalization in Rodin consists of 11 machines, 97 axioms, 28 proof obligations (POs) and 1 main theorem. About 60 percent of the POs were discharged automatically with Rodin, while the remaining 40 percent required manual assistance – mainly to prove that type definitions were called with parameters of the correct type. This is much like discharging TCCs (Type Correctness Conditions) in PVS.

To reduce the chances of introducing inconsistencies, we have successfully used the ProB model-checker [30] to find a valuation that makes all the above axioms true except for the ones pertaining to methods (including class constructors). Model-checking of methods timed out. Hence, we stated and successfully model-checked weaker axioms asserting the existence of states obeying the semantics. This is because our shallow embedding semantics does not account for the internal structure of predicates that ProB needs to model check the methods and constructors, e.g. to model check the relationship between states obeying a method precondition and states obeying a method postcondition.

6 Conclusion

The ability to transition from Event-B to JML while developing a software system has significant practical benefits: an abstract model of the system can be fully verified in Event-B and then translated to JML for implementation. This reduces the number of proof obligations that must be discharged by shortening the refinement chain, and allows programmers who are not familiar with Event-B notation and formal refinement techniques to produce a correct system implementation from the JML specification. Automating the translation from Event-B to JML greatly reduces the overhead associated with this approach and allows the soundness of the translation to be proven once, rather than being considered during each development effort.

The work presented in this paper proves the soundness of our translation under a precisely documented set of assumptions. In particular, we have shown that a JML class specification produced by the EventB2Jml tool is a refinement of the Event-B machine being translated. Conducting the proof in Rodin gives
a high degree of confidence in the correctness of the proof itself, allowing us to focus our attentions on axiomatizing the translation and the semantics of Event-B and JML in a concise and effective manner.

Formalising a proof in a tool is often a trade off between the level of detail the proof should provide and the feasibility of discharging it in an automated tool. In our earlier work on the definition of the $\text{EB2Jml}$ operator [14], Event-B types such as sets, functions and relations are represented using bespoke Java classes (with full JML specifications). The soundness proof presented in Section 5 relies on the correctness of the representation of Event-B mathematical types by respective JML types, and, indeed, attempting to represent those in the logic of Event-B would greatly increase the complexity of the proof. An alternative approach would be to use existing JML machinery [10,9] to separately verify that the JML representations do in fact have the same behaviour as the Event-B types that they represent.

We have discussed several additional simplifications and assumptions made in our formal model of Event-B machines at the beginning of Section 5. The assumption that states in Event-B and JML have the same representation is partially addressed in the previous paragraph. Additionally, in Java (and JML), two references can be aliased (refer to the same object) in a particular state. Modelling such states requires an extra level of indirection – typically one partial function is used to map identifiers to locations, and a second to map locations to values. However, the JML class specifications produced by our translation can not be used to create aliases, and so our state definitions need not be capable of modelling it.

We assumed that the body of an event is composed of a single assignment, although, in general, in Event-B, multiple assignments can be executed in parallel using the $\|\$ operator. In the specific case of our translation, the right-hand side of an assignment is always evaluated in the pre-state (due to the use of $\text{old}$ in the JML translation), so multiple assignments could be composed in any order in the semantics. In general, a parallel composition of assignments can be translated to sequential assignments using temporary variables. That is, the parallel composition $x := E \| y := F$ can be expressed as the sequence of assignments $\text{temp} := F \ ; \ x := E \ ; \ y := \text{temp}$. This approach permits translation of parallel assignments to notations (such as programming languages) that do not provide a mechanism for evaluating predicates in the pre-state. Considering Event-B machines with multiple variables, invariants and/or events requires a degree of extra machinery in the translation and proof, but would not change our fundamental approach or conclusions.

The five steps enumerated at the beginning of Section 5 outline a general approach for using an automated tool to prove the soundness of a translation between two formal languages, particularly when the semantics of the languages are expressed via transition systems. Figure 4 in Section 5.4 suggests a granularity level for those transitions in the underlying logic.

First, the syntactic constructs of both languages are represented in the logic of the automated tool. Choosing the right representation for those constructs and
the right level of detail will determine the level of complexity of the proof together with the number of proof-obligations that are to be discharged (the trade off between a deep and a shallow embedding). Second, the translation from the source to the target language is modelled in logic as axioms taking syntactic constructs from one language to the other. Third and fourth, the type semantics for the source and the target language are provided, and type constructors to build elements of those types are defined. Type states are defined as state transducers. Fifth, a soundness proof is enunciated as relating state transitions in the target language with state transitions in the source language. The level of granularity of those transitions affects the level of complexity of the proof. To simplify the proof, it may be useful to make (valid) assumptions about the representation of states in the transition system for the source and the target language. Choosing different representations for the states will certainly require constructing representations of both in the logic of the automated tool, and establishing a relationship between these representations. This would significantly increase the complexity of the proof.

It is true that for the approach just described in general (and for the proof presented in this paper in particular), what is actually being shown is the soundness of an axiomatization of the translation with respect to axiomatizations of the semantics of the source and target languages. This is a disadvantage of any approach based on shallow embedding – the logical mechanisms required to do the embedding do introduce possibilities for errors and inconsistencies. In terms of our translation, the translation rules and axiomatizations of those rules are given at a similar level of abstraction and the relationship between them should be immediately apparent. We do not know of a way to truly validate our axiomatizations of Event-B and JML semantics, but presenting the semantics in such a formal and unambiguous way does precisely document any assumptions that we have made and otherwise allows the reader to check the semantics against their own knowledge and understanding.

Future Work We are currently working on a translation from JML to Java, thus completing the translation from Event-B down to code. We will conduct another correctness proof for this new translation. For Java code generation, we envision a framework in which events, implemented as Java methods, are non-deterministically invoked by programming threads when event guards hold. Thus, event guards prevent updates of the system state. This can be implemented as a subroutine in which access to a critical section (the event action) is conditioned by the event guard [22]. Within this framework, the implementation of standard critical-section algorithms, e.g. Dekker’s [18] or Lamport’s bakery algorithm [28], ensure that any valid sequence of JML method executions (the critical section) correctly simulates the sequence of event triggering in the Event-B model that was translated. No additional correctness proofs need be conducted for this interaction as properties like mutual exclusion, absence of deadlocks and starvation for these algorithms have already been proved in literature.
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