\( \mu \text{CRL specification of event notification in JavaSpaces}^{\text{TM}*} \)

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\textbf{Abstract.} In this paper, we extend the formal specification of the JavaSpaces architecture presented in [18] with the event notification mechanism. Processes running on a JavaSpaces system can register their interest in incoming entries. The space informs the arrival of matching entries by sending events to the registered processes. We use \( \mu \text{CRL} \), a language that combines abstract data types with process algebra, to model a formal abstraction of this mechanism. The purpose of this work, in combination with the previous one, is to verify properties of the JavaSpaces technology and to allow automatic model checking of distributed applications built under it.

1 Introduction

The parallel composition of simple behavior agents can produce complicated systems. Distributed applications have to manage with the communication and synchronization between processes across heterogeneous networks, dealing with latencies, partial failures and system incompatibilities. Hence coordination architectures attempt to assist programmers at the difficult task of designing and implementing reliable distributed systems.

JavaSpaces\textsuperscript{TM} [16] technology is a Sun Microsystems Inc. coordination architecture, implemented as a Jini\textsuperscript{TM} [17] service. It gives support to two programming styles of processes coordination: the shared dataspace (Linda [8] like style) and a reactive style. External agents communicate by sharing objects through the space, by means of some basic primitives. They can basically write and look up objects but they can also express their interest in incoming entries, by registering using the \texttt{notify} primitive. Then the space is charged to inform the agents the presence of suitable entries by sending events. The external processes “react” to the arrival of new entries in the space.

In a previous paper [18], we studied the basic features of the shared dataspace style, now we are going to present the formal specification of the notification mechanism using \( \mu \text{CRL} \) [13, 11], a language which merges the standard process

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JavaSpaces

2 JavaSpaces

JavaSpaces is both an application program interface (API) and a distributed programming model. Agents can interact simultaneously with a shared dataspace of objects. The space handles the details of concurrent access to the data. Agents of applications are "loosely coupled", they do not communicate with each other directly but by sharing information via the common space. They use a small set of primitives described in Figure 1:

![JavaSpaces architecture overview](image)

Fig. 1. JavaSpaces architecture overview

A write operation places a copy of an entry into the space. Entries can be located by "associative lookup" implemented by templates. Processes find the
entries they are interested in by expressing constraints about their contents without having any information about the object identification, owner or location. A read request returns a copy of an object from the space that matches the provided template, or null if no object has been found. If no matching entries are in the space, then read may wait a user-specified amount of time (timeout) until a matching entry arrives in the space. ReadIfExists performs exactly like read but it only blocks if there are matching objects in the space but they have conflicting locks from one or more other transactions. Take and takeIfExists are the destructive versions of read and readIfExists: once an object has been returned, it is removed from the space.

The notify primitive is used to express interest in future incoming objects. The agent provides a template and the space will notify the agent when a matching object has arrived, by means of an event. Three entities are involved in the notification mechanism: The space is the source of events, it fires an event when an entry matches a registration. The destinations, called listeners, wait for the arrival of events and “react” to them. And the application process which register the listeners to be notified. The registration is done by the synchronous action notify based on the JavaSpaces specification [12].

```java
public interface JavaSpace {
    ...
    EventRegistration notify(Entry tmpl, Transaction txm,
        RemoteEventListener listener, long lease,
        MarshalledObject handback)
        throws RemoteException, TransactionException;
    ...
}
```

The primitive gets as arguments the template to match entries, the reference to a transaction, the reference to the remote event listener, the lease and a handback used to pass information from the application process to the listeners. The space returns an `eventRegistration` object, which includes the registration identification number (the space assigns a identification number to any new registration), the granted lease and the initial sequence number for events generated from the notify registration. Every matching entry will increase by one the sequence number of the registrations. And newly generated event will contain a sequence number greater than the previous one.

JavaSpaces also provide support to leasing and transactions, from the Jini architecture [17]:

JavaSpaces supports a transactional model ensuring that a set of grouped operations are performed on the space atomically, in such a way that either all of them complete or none are executed. Transactions affect the behavior of the primitives, e.g. an object written within a transaction is not externally accessible until the transaction commits, the insertion will never be visible if the transactions aborts. Transactions provide a means for enforcing consistency. Transactions in JavaSpaces preserve the ACID properties: Atomicity, Consistency, Isolation and Durability.
JavaSpaces allocates resources for a fixed period of time, by associating a lease to the resource. The lease model is beneficial in distributed systems where partial failures can produce waste of resources. The space determines the time during which an object can be stored in the repository before being automatically removed. Also, transactions are subject to leasing, an exception is sent when the lease of a transaction has been expired. Leases can always be renewed or canceled.

In the paper [18] we have presented the $\mu$CRL specification of the primitives: write, read, take, takeIfExists and readIfExists, leases and transactions. Now we are going to focus on the notify operation.

To know more about JavaSpaces, please consult the references [12, 16].

3 Introduction to $\mu$CRL

A $\mu$CRL specification is composed by two parts. First, the definition of the data types, called sorts. A sort consists of a signature in which a set of function symbols, and a list of axioms are declared. For example, the specification of the booleans (Bool) with the conjunction operator (and) is defined as follows:

\[
\begin{align*}
\text{sort} & \quad \text{Bool} \\
\text{func} & \quad T,F:\rightarrow \text{Bool} \\
\text{map} & \quad \text{and}: \text{Bool} \times \text{Bool} \rightarrow \text{Bool} \\
\text{var} & \quad b: \text{Bool} \\
\text{rew} & \quad \text{and}(T, b) = b \\
& \quad \text{and}(F, b) = F
\end{align*}
\]

The keyword func denotes the constructor function symbols and map is used to declare additional functions for a sort. We can add equations using variables (declared after rew and var) to specify the function symbols. The declaration of the sort Bool must be included in every $\mu$CRL specification because booleans are used for modeling the guards in the “if-then-else” construction.

The second part of the specification consists of the process definition. The basic expressions are actions and process variables. Actions represent events in the system, are declared using the keyword act followed by an action name and the sorts of data with which they are parameterized. Actions in $\mu$CRL are considered atomic. There are two predefined constants: $\delta$ which represents deadlock and $\tau$ which is a hidden action. Process variables abbreviate processes, and are used for recursive specifications. Process operators define how the process terms are combined. We can use:

- The sequential, alternative and parallel composition ($.,+,\parallel$) process operators.
- sum ($\Sigma$) to express the possibility of infinite choice of one element of a sort.
- The conditional expression “if-then-else” denoted $p \leftarrow b \rightarrow q$, where $b$ is a boolean expression, $p$ and $q$ process terms. If $b$ is true then the system behaves as $p$ otherwise it behaves like $q$. 

\[
\begin{align*}
\text{sort} & \quad \text{Bool} \\
\text{func} & \quad T,F:\rightarrow \text{Bool} \\
\text{map} & \quad \text{and}: \text{Bool} \times \text{Bool} \rightarrow \text{Bool} \\
\text{var} & \quad b: \text{Bool} \\
\text{rew} & \quad \text{and}(T, b) = b \\
& \quad \text{and}(F, b) = F
\end{align*}
\]
They keyword **comm** specifies that two actions may synchronize. If two actions are able to synchronize we can force that they occur always in communication using the operator $\bigodot_H$. The operator $\tau_I$ hides enclosed actions by renaming into $\tau$ actions. The initial behavior of the system can be specified with the keyword **init** followed by a process term:

$$\text{System} = \tau_I \bigodot_H (p_0 \parallel p_1 \parallel \ldots)$$
$$\text{init System}$$

4 \hspace{1em} \mu\text{CRL Specification}

The space is modeled as a single process called *javaspace*. External agents are implemented as separate processes executed in parallel with the space. A JavaSpaces system is specified in $\mu$CRL as follows:

$$\text{System} = \tau_I \bigodot_H (\text{javaspace}(...) \parallel \text{external}_P (id_0 : \text{Nat}, \ldots) \parallel \text{external}_P (id_1 : \text{Nat}, \ldots) \parallel \ldots)$$

The arguments of the *javaspace* process represent the current state of the space. They are composed by: stored objects, active transactions, the current time, active operations, notify registrations, et cetera... External processes interact with the space by means of a set of synchronous actions, derived from the JavaSpaces API. Every process has a unique identification number used by the space to control the access to the common repository. Processes use the sort *Entry* to encapsulate the shared data. In the JavaSpaces specification, an entry corresponds to a serializable Java™ object which implements the public interface *Entry* (with some other restrictions). In our model, entries are represented by a *sort*. Users can define their own data structure according to the application requirements. The insertion of a new entry into the space is done with the action *write* which has four arguments: the process identification number of the sort *Nat* (naturals), the entry of the sort *Entry*, the lease of naturals and the reference to a transaction (null if it is not submitted to any one). When the space receives a write request, it automatically encapsulates the entry, with its lease and the reference to the transaction, in a new data sort (*Object*) and stores it in the database which has the structure of a *Set*.

Look up primitives could be classified as: *destructive* and *non-destructive*, depending on whether the item is removed or not after the execution of the action, and in *blocking* and *non-blocking* depending on whether the process waits until it receives the requested item. We can invoke destructive look ups (*take*) or non-destructive (*read*), setting up the time during which the action blocks.

The JavaSpaces specification says that a look up request searches in the space for an *Entry* that matches the template provided in the action. If the match is found, a reference to a copy of the matching entry is returned. If no match is found, *null* is returned. We do not use templates to model the matching operation but by adding to every invocation one predicate, as argument, which determines if an *Entry* matches or not the action. This predicate belongs to the
`\( \mu \text{CRL Specification} \)

**sort** [Query](#) defined by the user according to the specification of the [Entry](#). The sort must include the operator [test](#) used to perform the matching. An entry of the space will match a look up action if it satisfies the associated [test](#) predicate. The look up operations are not atomic. They are done by two synchronous actions; first the process makes the request and blocks waiting for an entry or for the timeout expiration. First, the space stores this request in a set with other pending requests and afterward the space returns a matching entry or the null value.

The behavior of all the primitives would be slightly different depending on whether they are executed under a transaction or not. Before focusing on the [notify](#) primitive let’s see a small example of code illustrating the presented operations. The example is a recursive process which renames entries of type \( A \) to type \( B \). It performs the operation under a transaction leased for one time unit. If the timeout of the transaction expires the space raises an exception and sent it to the process by means of a synchronous action (exception), then the process deadlocks:

```plaintext
proc ren(id:Nat) =
  \sum_{trc:Nat} (create(id, trc, S(0))
  .(take(id, trc, FOREVER, isTypeA) + Exception(id, trc), \delta)
  .\sum_{e:Entry} ((Return(id, e) + Exception(id, trc), \delta)
  .(write(id, renameToB(e), trc, FOREVER)+ Exception(id, trc), \delta))
  .(commit(id, trc) + Exception(id, trc), \delta))
  .ren(id), \delta
```

Now, we are going to focus on the specification of the notify mechanism introduced in Section 2.

For simplicity, we have abstracted away the lease, the transaction and the handback but we will comment the inclusion of the first two fields later in this section. The template is replaced by a query. We assume the registration is done atomically, thus no events can be fired between the begin of the registration and its return. Therefore the initial sequence number of events will be zero. Due to these abstractions, the space only returns a single value representing the registration identification number. This operation is performed reliably so it cannot throw any exception. The action signature is:

**sort** [Nat](#), [Query](#)

**act** notify: [Nat](#)×[Nat](#)×[Query](#)×[Nat](#)

The arguments are: the process identification number, the listener identification number, the query and the event registration identification number (provided by the space).

When the space synchronizes with a [notify](#) action, it stores the registration in a set. For each newly written entry it will check every registration to know whether it has to be notified or not. In other words, the space marks the registrations whose query matches the new entry. It also increments by one the event sequence number. The specification says that the space makes a “best effort”
to deliver the notifications, a notification event will be *eventually* sent to the registered listeners. The space does not guarantee the generation of an event for every matching entry, so several matching entries can be stored before the space decides to fire a message. The sequence numbers are useful to keep track of the events, as we will see on a small example in Section 5.

An event listener is an object that reacts to the reception of an event and that may be running remotely. The listener has a method (*notify*) invoked whenever it receives a notification event. According to the JavaSpaces specification the *notify* call is synchronous so the space waits on a listener until the call finishes, but the JavaSpaces implementations are multi-threaded hence many different *notify* calls can be done concurrently. We modeled the *notify* operation with our single *javaspace* process, assuming that we have an implementation with enough threads to manage all the notifications of the system. The μCRL space delivers the event and doesn’t wait until the end of the method call of the listener. This policy will not be admissible if there are too many listener registrations or if the *notify* methods are very slow (block the space for long periods) or never return. Our model would help programmers to take care about preserving the desirable behavior of the system, for example we will show one application in Section 5 the detection of a problem in a listener which arrives to a non-desired blocked state.

The event sent by the space contains some data values. It includes the registration identification number, to allow a listener to distinguish the event as belonging to a particular registration and the sequence number of events, which can be used by listeners to know the number of events occurred from last notification.

In our model, listeners are going to be modeled as separate processes. μCRL does not allow the instantiation of processes on running time so listeners have to be defined at the beginning, according to the needs of the application. A listener has the following structure:

```plaintext
proc listener(id:Nat, d0:D, ..., dn:D) =
    \sum_{registrationID:Nat} \sum_{seq:Nat} .Notify(id, registrationID, seq)
    .do_work
    .listener(id))
```

Where d0:D, ..., dn:D are the user defined arguments, and _Notify_ the action for receiving the event. The _do_work_ operation may be composed of any computation or any communication with other processes or with the space.

Messages travel over the network from the event source (the space) to the event destination (the listener); they are not delivered instantaneously nor reliably. Hence events may be lost and never reach their destinations. They may also arrive unordered because events can follow different paths. The event source can always duplicate messages because it cannot be sure whether the delivered events have arrived or not. To model this non-deterministic behavior, we specify

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1. Do not confuse with the registration notify method.
a separate process which represents the network situated between the source and the destination. This process stores the events in a fifo list, and can always:

- Receive: The network process receives and event from the space by means of the synchronous action \_\_Notify.
- Loose: It removes the first object of the list.
- Swap: It changes the order of the first two events that have the same destination.
- Duplicate: It replicates the first element of the list.
- Deliver: The networks dispenses an event to a listener using the action \_\_notify.

We parameterized the network process with a field counting the number of errors (looses, duplications and swaps). To keep finite the system we only allow a maximum number of errors. A reliable network would have a maximum number of errors equal to zero.

The complete system is composed of the parallel composition of the application processes, listeners, the space and the network. Figure 2 illustrates the model.

![Network Architecture](image)

**Fig. 2.** Notification architecture

We can also add leasing to the registration mechanism. We proceed in the same way as for the look up primitives. The application process passes the requested lease to the space, it includes this value in a data field of the registration object. The space manages a centralized clock implemented as a discrete counter. The `javaspace` process increments this clock arbitrarily. Using this counter we can manage the expiration of the leases. When the registration lease expires the space automatically removes the object from the data base. Listeners can receive
events even if the registration has been removed, because the messages may be
delayed on the network.

Notify can also be joined to a transaction. The space will send events when
a matching entry is written under the same transaction of the registration or
under the null transaction. If a transaction expires the joined registrations will
be removed. We have not implemented these two issues (transactions and leasing)
for the notify primitive, but according to its specification for the other primitives
we foresee no major difficulties to do it. This concludes the presentation of the
μCRL model, now let’s analyze a simple application.

5 Example

In this section we are going to illustrate the use of the proposed specification to
model check JavaSpaces applications by analyzing a simple example. The system
consists of a process which registers a listener, expressing interest in any new
data of the type message. When the listener receives the event, it just takes the
message and prints “Hello World” [see the example in Chapter 8 of “JavaSpaces
Principles, Patterns, and Practice” [12]]. First we specify the sort Entry, which
only has two possible values the compulsory null entry, and the message (we
don’t care about its content). The μCRL code is as follows:

```
sort Entry
func entryNull:→Entry
  message: →Entry
map eq: Entry×Entry→Bool
var e: Entry
rew eq(entryNull, entryNull) = T
  eq(message, message) = T
  eq(entryNull, message) = F
  eq(message, entryNull) = F
```

We define two queries: any which matches any entry and isMessage which matches
the entries of type message. Let’s see the code:

```
sort Query
func any: →Query
  isMessage: →Query
map test: Query×Entry→Bool
  eq: Query×Query→Bool
var e: Entry
rew test(any, e) = T
  test(isMessage, message) = T
  eq(any, any) = T
  eq(isMessage, isMessage) = T
  eq(any, isMessage) = F
  eq(isMessage, any) = F
```
The user application is composed by two processes. Apps executes the action notify registering the listener and the listener, that first gets the event and then tries to take the entry from the space. If the take is successful it does the action Hello World. Note that we have simplified the primitives take and write by removing the lease and the transaction. The code is:

\[ \text{proc} \quad \text{apps(id: Nat, listenerID: Nat) = } \]
\[ \sum_{\text{registrationID: Nat}} (\text{notify(id, listenerID, isMessage, registrationID)}) \]
\[ \cdot \text{write(id, token)}.\delta \]

\[ \text{proc} \quad \text{listener(id: Nat) = } \]
\[ \sum_{\text{registrationID: Nat}} (\sum_{\text{seq: Nat}} (\_\text{Notify(id, registrationID, seq)})) \]
\[ \cdot \text{take(id, isMessage)} \]
\[ \cdot \text{waiting} \]
\[ \cdot \sum_{e: \text{Entry}} (\text{Return(id, e)}) \]
\[ \cdot \text{HelloWorld} \]
\[ \cdot \_\text{endNotify(id, registrationID, seq)} \]
\[ \cdot \text{listener(id)} \]

Finally, the complete system is composed by the parallel composition of the space, the apps process, the listener and the network, which is allowed to commit one error.

\[ \text{System} = \partial_{\{\text{write, Write, notify, Notify, \_notify, \_notify, \_Notify, \_Notify, \_Notif, \ldots}\}} \]
\[ (\text{javaspace}(0.0, \text{em}N, \text{emA}.0)|\text{Network}(\text{emE}.0, \text{S}(0))||\text{apps}(0, \text{S}(0))||\text{listener}(\text{S}(0))) \]

To each \(\mu\text{CRL}\) specification belongs a labeled transition system (LTS) being a directed graph, in which the nodes represent states and the edges are labeled with actions. If this transition system has a finite number of states the \(\mu\text{CRL}\) tool set can automatically generate this graph. Subsequently, the C\(\text{ESAR A}\)D\(\text{ÉB} \text{ARAN DEVELOPMENT PACKAGE (CADP)}\) can be used to visualise and to analyse this transition system. Figure 3 shows the generated LTS of the simple Hello World application where the action \(N\) corresponds to the communication between the notify action of the application process and the Notify action of the space \(W\) to the write actions, \(\_N\) corresponds to send an event from the space to the network \(\_N\) to deliver it from the network to the listener. \(T\) corresponds to a take request and \(Rt\) is the return of the take. Duplicate, loose, Hello World, waiting and endNotify are external actions informing about the execution of the system. Remark that the action endNotify is just a “printed” message, listeners do not synchronize with the space at the end of the notify invocation.

We can see in the figure 3 a desirable execution following the path: 0-1-2-3-4-7-9-11-13-15) and two undesired behaviors. The first is when the network looses the data (path: 0-1-2-3-5), thus the listener doesn’t receive the message. The other is when the network duplicates the event(0-1-2-3-6-8-10-12-14-15-16-17-18-19-20), then listener tries to take two times the message. In this case the listener gets blocked waiting for a return that will never happen unless another
process writes a new message. We can avoid the second undesired behavior by checking the event sequence number before trying to perform the take primitive. This is modeled with the following code:

\[
\text{proc } \text{listener}((id: \text{Nat}, \text{last: \text{Nat}}) = \\
\quad \sum_{\text{registrationID: \text{Nat}}} \sum_{seq: \text{Nat}} \text{(.Notify(id, registrationID, seq)} \\
\quad \text{.}(\text{take(id, isMessage)} \\
\quad \text{.waiting} \\
\quad \sum_{e: \text{Entry}} (\text{Return(id, e)}) \\
\quad \text{.HelloWorld } \langle \text{gt(seq, last)} \text{ do nothing} \rangle \\
\quad \text{.endNotify(id, registrationID, seq)} \\
\quad \text{.listener(id))})
\]

The listener only tries to take the message if the sequence number \(seq\) is greater than the sequence number of the last notification \(last\), otherwise it assumes that the event has been duplicated and finishes.

We can automatically verify some properties of the system using the Evaluator tool from the CADP package. These properties are expressed in temporal logic. We used the regular alternation-free \(\mu\)-calculus formulas [15]. For example, the following formula means that every notify invocation of a listener finishes, in other words: after a \(\_N\) there is always an endNotify with the same arguments:

\[
[\text{true}*.\_N(\ast)] \mu X. (\langle \text{true} > \text{true and } [\text{not } \text{endNotify} (\langle \ast \rangle)] X)
\]
This formula does not hold for the first example of listener. The evaluator analyzes it and gives the counter example corresponding to already pointed path. However the second listener, which checks the sequence number of events satisfies the property.

6 Related Work

As we said, this work is an extension of the [18]. Our information of JavaSpaces is based upon the book [12], and the documentation from Sun on JavaSpaces [16] and Jini [17]. The latter document describes a.o. the concepts of leasing, transactions and distributed events. The basic ideas of JavaSpaces go back to the coordination language Linda [8].

Some work on the formalization of JavaSpaces (or other Linda-like languages) exist. notably [4, 5, 6, 7]. In these papers, an operational semantics of JavaSpaces programs is given by means of derivation rules. In fact, in this approach JavaSpaces programs become expressions in a special purpose process algebra. Those authors aim at general results, i.e. comparison with other coordination languages, expressiveness, and results on serializability of transactions. Verification of individual JavaSpaces programs wasn’t aimed at.

Although we also take an operational approach, our technique is quite different. We model the JavaSpace system, and the JavaSpaces programs as expressions in the well-known, general-purpose process algebra, μCRL [13]. This allows us to use the existing μCRL tool set [2] and the CADP tool set [10] for the verification of individual JavaSpaces programs. In our model, the JavaSpaces programs communicate with the JavaSpaces system synchronously.

Our technical approach is similar to the research in [9, 14]. In these papers, programs written under the Splice architecture [3] are verified. Both papers give an operational model of Splice in μCRL, and use the μCRL and CADP tool sets to analyse Splice programs. One of the main purposes of the Splice architecture is to have a fast data distribution of volatile data. To this end, the data storage is distributed, as opposed to the central storage in JavaSpaces. In Splice, data items are distributed by a publish/subscribe mechanism. Newer data items simply overwrite outdated items.

7 Conclusion

In this paper we studied the specification of the notify mechanism of the JavaSpaces architecture. We have found several difficulties in interpretation that we tried to solve. Some of these problems are solved in the implementation of JavaSpaces but not in its specification.

First, the specification says that an event can be duplicated by the event source. This issue is source of several questions: How and when does the space decide to send twice the same message? Has the notify call a timeout? Can listeners be notified during a notification? Other problem comes from the interpretation of “best effort”; the space will “eventually” send a event after a
write. But when does the space send a event? and when does it compress several matches in one notification?

The notify call is “synchronous”, so the space blocks until the end of the remote method. Which actions are listeners allowed to do in the notify method? What will happen if a listener never returns? What will be the difference between a single-threaded and a multi-threaded space?

We attempted to solve the unclear details by making assumptions about the behavior of the system. Our informations are not only based on the JavaSpaces specification, sometimes ambiguous, but also in the archives of the discussion group where some of these have been treated. See, for example:

http://archives.xml.mun.com/cgi-bin/etd241d900/etd.jsp spacem-usesm?=3466&ID=04%0D%717=1

http://archives.xml.mun.com/cgi-bin/etd241d900/etd.jsp spacem-usesm?=3466&ID=04%0D%717=1

The last part of the paper is dedicated to the study of a very simple JavaSpace applications. Although we cannot verify the correctness of the proposed model we can see, in small examples, that the behavior corresponds to JavaSpaces specification. Together with the µCRL simulator this provides some validation of the model. We also present some ideas of how to verify properties of applications. In the same way we can study more complex problems.

The µCRL model of the notification mechanism may be used not only to model check JavaSpaces applications but also to study the architecture itself and resolve all kinds of unclear or ambiguous points.

References


Conclusion